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IRRIGATION PAPERS

OF THE

UNITED STATES GEOLOGICAL SURVEY

No. 42

THE WINDMILL: ITS EFFICIENCY AND ECONOMIC USE, PART II.—Murphy

WASHINGTON
GOVERNMENT PRINTING OFFICE
1901

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

THE WINDMILL:

ITS EFFICIENCY AND ECONOMIC USE

PART II

By EDWARD CHARLES MURPHY

WASHINGTON

GOVERNMENT PRINTING OFFICE

1901

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DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
DIVISION OF HYDROGRAPHY,
Washington, January 14, 1901.

SIR: I have the honor to transmit herewith a manuscript entitled The Windmill: Its Efficiency and Economic Use, Part II, by Edward Charles Murphy, formerly professor of civil engineering in the University of Kansas, and to request that it be published in the series of Water-Supply and Irrigation Papers.

This manuscript is a continuation of the material published as Paper No. 41, it being necessary to divide the manuscript on account of the limitation imposed by law of 100 printed pages for each pamphlet.

Very respectfully,

F. H. NEWELL,
Hydrographer in Charge.

Hon. CHARLES D. WALCOTT,
Director United States Geological Survey.

THE WINDMILL: ITS EFFICIENCY AND ECONOMIC USE.

PART II.

By Edward Charles Murphy.

EXPERIMENTS BY WRITER—CONTINUED.

In Part I of this paper, published as Water-Supply and Irrigation Paper No. 41, will be found a classification of windmills, a discussion of regulating devices, a synopsis of early experiments with windmills, and a discussion of the writer's experiments with pumping mills. This part (II) of the paper contains the results of the writer's experiments with power mills, a comparison of pumping mills with power mills, and discussions of various facts developed by the tests, together with a comparison of the writer's experiments with those of other experimenters, and the economic considerations of the subject.

POWER MILLS.

The power mill differs essentially from the pumping mill in that the latter gives a reciprocating motion to a pump piston, while the former gives a rotary motion to a vertical shaft, and this, in turn, to a horizontal shaft, which drives the grinder or other machine. The mechanism by which this is accomplished in the Aermotor is shown in figs. 33 and 34. The small plane cogwheel makes three revolutions to one revolution of the wind wheel, and the small beveled cogwheel makes two revolutions to one revolution of the small plane wheel; so that the vertical shaft makes six revolutions to one revolution of the wind wheel; or, as we say, the shaft is geared forward 6 to 1. The two beveled cogwheels of the foot gear (fig. 34) change the motion around a vertical axis to a motion around a horizontal axis without changing the rate of speed. In fig. 7, Part I, which shows the pumping mill, it will be seen that the large cogwheel which gives the up-and-down motion to the piston makes one revolution to each 3.3 revolutions of the wind wheel, or that the pump is geared back 3.3 to 1; so that the vertical shaft of a power mill makes twenty revolutions to one stroke of a pump worked by a pumping mill the wind wheel of which is running at the same rate as that of the power mill. The term "geared mill" is sometimes applied to power mills, but inappropriately, since the pumping mill also is geared. The latter is geared back, the former is geared forward.

Power mills are heavier than pumping mills. They ordinarily do more work and carry heavier loads than the latter. The load on the pumping mill is constant for all wind velocities, but it may be varied in the power mill. The grinder is made so that as the speed increases the quantity of corn which enters increases, and thus the load and work done are increased. The mill is expected to do three or four kinds of work—for example, pump water, shell and grind corn, and turn a grindstone. In a light wind the pump only can be worked, but as the wind increases one after another of the three other machines can be set at work, and thus the load be suited to the velocity of the wind and the mill be made to do the maximum amount of work. Power mills are not made smaller than 12 feet in diameter, for the reason that a small size will not give power enough to be of account except for pumping. The ordinary steel power mills are 12 feet, 14 feet, and 16 feet in diameter.

The power that a windmill is capable of developing can be determined better from a power mill than from a pumping mill, because the efficiency of the pump—which may be anywhere from 20 to 85 per cent—is eliminated, and because the load on the mill can be varied at will, and thus the effect of the load on the power of the mill be determined for different wind velocities.

METHOD OF TESTING.

The power was measured by the use of a Prony friction brake placed on an iron pulley on the foot gear or horizontal shaft. The brake was of wood, and had an arm 3 or 4 feet long. Near the end of this arm was fastened a spring balance reading to quarters of a pound. By turning the nuts on the brake the spring balance could be made to read any desired amount. As the brake on the pulley was tightened, the reading of the spring balance was increased and the number of revolutions of the shaft decreased. The brake is shown in Pl. XV. The speed of the shaft was found in one of three ways—whichever was most convenient. A small electric device was used whenever it could conveniently be attached to the wind wheel. The clicks of this instrument could easily be counted, and gave the number of revolutions of the wind wheel for each half mile of wind movement. A speed counter was used, but did not prove satisfactory. Whenever the electric device could not conveniently be employed, the number of revolutions of the wind wheel was found by counting the revolutions of a mark on the wind wheel as reflected in a mirror conveniently placed.

To illustrate: If u is the number of revolutions per minute of the brake pulley as found from the revolutions of the wind wheel per half mile of wind, L the load in pounds as read from the spring balance, and R the length of the arm, then the useful work, in foot-pounds per minute, is—$W = 2\,\pi\,R\,u\,L$, and the horsepower is—H. P. $= 2\,\pi\,R\,u\,L \div 33{,}000$.

The number of revolutions per minute of wind wheel was found for each mill for from two to six different brake loads, for wind velocities as small as would keep the mill working for the particular load used

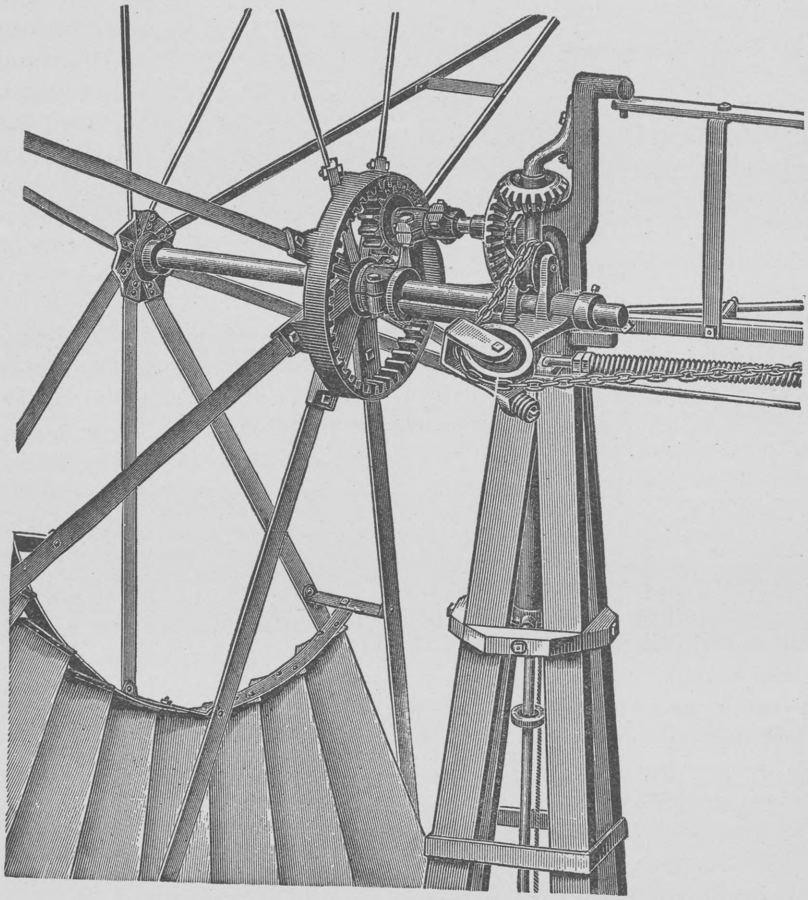


FIG. 32.—Working parts of mill No. 26—14-foot Perkins.

up to about 25 miles an hour. That is, the reading of the spring balance was kept as nearly constant as possible until we had obtained points and a curve like that shown in fig. 10. Then the load was changed and the tests continued in the same way, getting another curve. From these curves the number of revolutions of wind wheel per minute for different loads and wind velocities was easily found, as before indicated. These are given in the table of results for each mill tested, and in many cases are also shown by diagram. The horsepower of any mill for different loads and velocities is easily found by the foregoing formula. These are given in the tables of results of tests, and are also shown by diagrams.

MILLS TESTED.

Mill No. 26.—This is a 14-foot Perkins steel power mill on a 40-foot steel tower, made by the Perkins Windmill Company, of Mishawaka, Indiana. The working parts are shown in fig. 32. The wind wheel has 32 curved sails, each 41 by 14.25 by 7.75 inches, set at an angle of 31° with the plane of the wheel. The shaft is geared forward 6 to 1. The radius of the brake pulley was 5 inches, the length of brake arm 33.5 inches. This mill was tested twice. Between the dates of testing some repairs were made to the shafting, causing the cogwheels to bind less tightly. The following figures are those obtained from the second test. The mill had been in use only about one year, and showed very poor workmanship. The results of the test are as follows:

Results of test of mill No. 26—14-foot steel Perkins.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Useful horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
6	645	------	------	16	31	48	------	------	0.313	0.609	0.937

Mill No. 27.—This is a 12-foot Aermotor on a 30-foot steel tower. The wind wheel is like that of mill No. 3 (see pp. 29 to 30, Part I). The horizontal shaft is geared forward 6 to 1. Fig. 33 shows the working parts, and fig. 34 the foot gear. The brake pully was 9.5 inches in diameter and was fastened to the foot gear at *a* in fig. 34. The brake arm was 35.25 inches in length. The mean temperature during the test was 46° F., and the mean barometric pressure 28.9 inches. The results of the tests are as follows:

Results of tests of mill No. 27—12 foot Aermotor.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Useful horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	30	49	63	75	87	------	------	------	------	------
2	222	16	43	57	70	81	0.089	0.285	0.386	0.458	0.523
4	444	------	23	48	65	77	------	0.303	0.653	0.890	1.02
6	666	------	------	12	50	72	------	------	------	1.03	1.45

The revolutions of wind wheel per minute for the four brake loads 0, 2, 4, and 6 pounds, respectively, are shown in fig. 35. The pull necessary to overcome the frictional resistance was found by standing on the platform of the mill and slowly turning the wind wheel around with a spring balance. This was checked by winding a

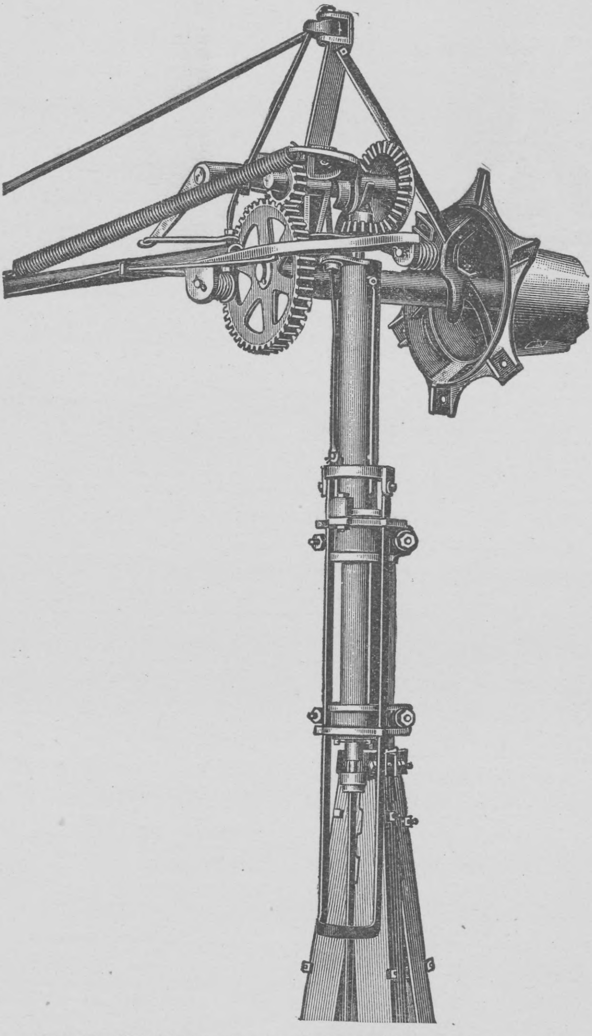


FIG. 33.—Working parts of mill No. 27—12-foot Aermotor.

cord around the circumference of the wind wheel, and, standing on the ground, moving the wheel when there was no wind by pulling on the spring balance attached to the cord. A pull of 1.25 pounds applied at the circumference was sufficient to overcome this resistance at a low velocity. The work done in overcoming this resistance is $1.25 \times 2\pi \times 6 = 47.1$ foot-pounds per revolution. The work done per revolution of wind wheel per pound on the brake arm is—$2\pi \times 35.25 \times 6 \div 12 = 111$ foot-pounds. The ratio of these is $47.1 \div 111 = 0.425$ pound. Hence a brake load of 0.425 pound is equivalent to the friction load.

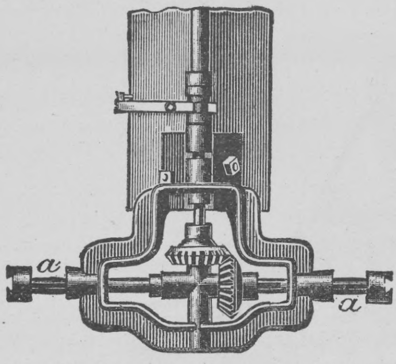


FIG. 34.—Foot gear of mill No. 27—12-foot Aermotor. *a* indicates point where brake pulley was attached.

The effect of each additional 2 pounds load on the brake in reducing the speed of the wheel at different wind velocities is clearly shown here. It is seen that an added load makes a greater proportionate reduction in the speed when the velocity is low than when it is high. Thus, in an 8-mile wind the addition of 2 pounds to the load reduces the speed 50 per cent, while in a 25-mile wind the same load reduces the speed only about 7 per cent.

It will be seen that for wind velocities above a certain amount, with the load not too great, each additional pound of load reduces the speed of the wheel by about the same amount. For example, in a 25-mile wind the addition of 2 pounds changes the speed from 87 revolutions to 81 revolutions. The addition of 2 pounds more changes

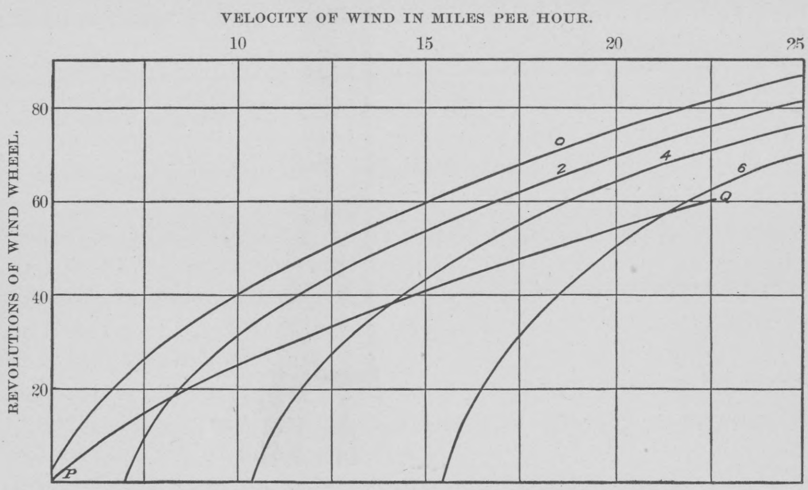


FIG. 35.—Diagram showing revolutions of wind wheel of mill No. 27—12-foot Aermotor. Curve marked 0 is for no brake load; curve marked 2 is for a brake load of 2 pounds; curve marked 4 is for a brake load of 4 pounds; curve marked 6 is for a brake load of 6 pounds; curve *PQ* is speed curve for maximum power.

the speed from 81 revolutions to 77 revolutions. It will be seen that as the load increases the increment of wind velocity necessary to start the mill increases more rapidly than the increment of loading. That is, the 0-pound load curve starts in about a 4.5-mile wind, the 2-pound curve in about a 7-mile wind, the 4-pound curve in about a 10.5-mile wind, and the 6-pound curve in about a 15.5-mile wind. The difference between these starting velocities is constantly increasing. A diagram was platted showing the horsepower of this mill for the 2-pound, 4-pound, and 6-pound brake loads. The curves showed that for any brake load the power of the mill increased rapidly as the wind velocity increased, and that it reached a maximum for some velocity greater than 30 miles an hour. As the load increased the velocity required to start the mill increased rapidly and the curve became steeper. For a given wind velocity the power increased rapidly as the load increased. For a velocity of 25 miles an hour the power was nearly proportional to the load for loads of less than 6 pounds. It showed that when the velocity was less than 12 miles an hour a 4-pound load was too great, and when it was less than 19 miles an hour a 6-pound load was too great. It showed also that the efficiency decreased as the wind velocity for a given load increased, and that it increased as the load increased. The efficiency for a load of 2 pounds and a wind velocity of 9 miles an hour was 40 per cent. At 14 miles an hour and with a 4-pound load it was 36 per cent. If the load at that velocity was reduced to 2 pounds, the efficiency was reduced to 24 per cent. Finding the efficiency by using the wind area (area of circle 12 feet in diameter) instead of the sail area, as is sometimes done, the foregoing efficiency of 40 per cent with a 2-pound load in a 9-mile wind became 26 per cent.

The results for this mill will be discussed from a mathematical point of view further on.

Mill No. 28.—This is a 16-foot Althouse wooden power mill manufactured by Althouse, Wheeler & Company, of Waupun, Wisconsin. It is shown in fig. 36. The axis of the wind wheel is 32 feet above the ground and 15 feet above the roof of a near-by blacksmith's shop. The wind wheel has 130 sails, each 48 by 4 by 1.5 inches, set at an angle of 32° to the plane of the wheel. Two half sails are missing and two others are slightly injured, making a loss of about one and a half sails. The horizontal shaft, which works a sheller, grinder, emery wheel, and wood saw, is geared forward 8.377 to 1. A pull of from 7 to 13 pounds at a distance of 6 feet from the center was necessary to start the mill, showing it to be a hard-running one. The brake pulley was 8 inches in diameter, the brake arm 3.5 feet long. A second visit to this mill was necessary in order to get results for high velocities. During the interval between the tests a 510-pound fly wheel was put on the shaft, which steadied the motion of the mill somewhat. The owner is well pleased with the action of this balance wheel. Single measurements of the power of this mill for the same load and wind velocity differ considerably. It is very evident that this mill is not high enough; if it were 30 or 40 feet higher it would give better results. It is with the aid of better results obtained from tests of other mills of similar make that we are able to give the results in the following table and in the diagrams.

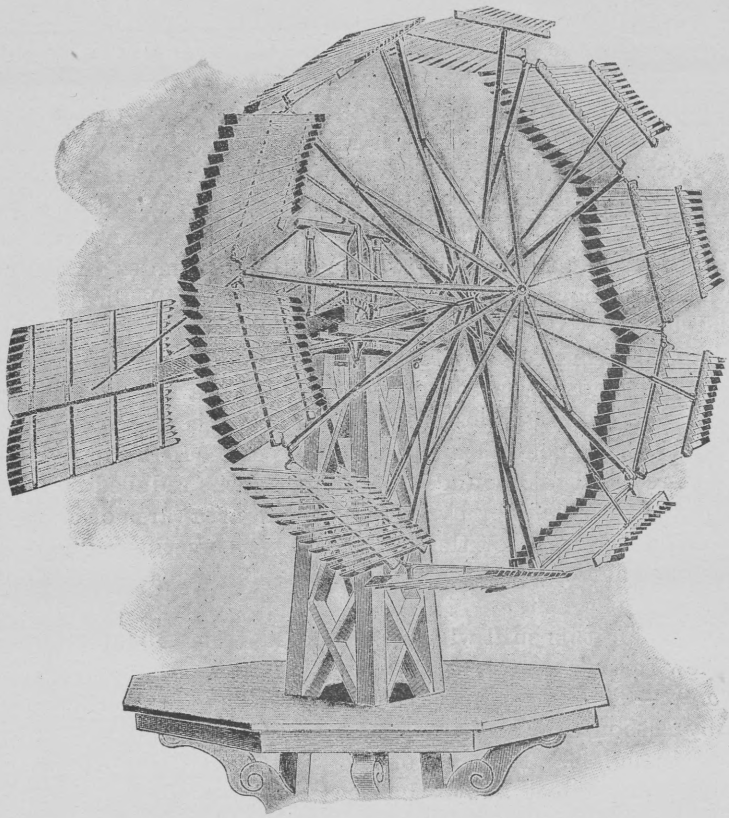


FIG. 36.—View of mill No. 28—16-foot wooden Althouse.

Results of tests of mill No. 28—16-foot wooden Althouse.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	13	23	30	36	40	------	------	------	------	------
1¾	427	------	20	27	31	36	------	0.26	0.35	0.40	0.46
G.	------	------	5	13	20	28	------	------	------	------	------
5¾	914	------	------	19	23	27	------	------	0.52	0.64	0.75
8¾	1,462	------	------	8	13	15	------	------	0.35	0.60	0.67

Fig. 37 shows the number of revolutions per minute of the wind wheel of this mill for the brake loads 0, 1.75, 5.75, and 8.75 pounds, and for grinder load. The curve for the grinder load is a nearly straight line. This is due to the fact that the grinder is constructed so that as its speed increases the amount of corn it receives increases; thus the load increases automatically as the wind velocity increases. By comparing these speed curves, as they may be called, with those of fig. 35, for the Aermotor, it will be seen that the speed of the latter is much greater than that of mill No. 28.

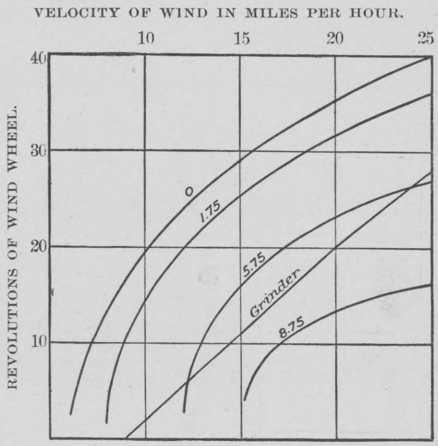


FIG. 37.—Diagram showing revolutions of wind wheel of mill No. 28—16-foot wooden Althouse. Curves marked 0, 1.75, 5.75, 8.75, and grinder are for brake loads of 0, 1.75, 5.75, and 8.75 pounds, respectively, and for grinder load.

Fig. 38 shows the horsepower of this mill for three brake loads—1.75 pounds, 5.75 pounds, and 8.75 pounds. The latter load is too great for the mill. By comparing the results for this mill with those for the 12-foot Aermotor (fig. 35) it will be seen that the latter mill is superior to the 16-foot wooden mill.

Mill No. 29.—This is a 16-foot Aermotor like that shown in Pl. XV. It is manufactured by the Aermotor Company, of Chicago, Illinois. The tower is of wood, 42 feet to the axis of the wheel. The wind wheel has 18 curved sails, each 59 by 25.75 by 10.5 inches, set at an angle of 30° to the plane of the wheel. It is used for shelling and grinding corn and for working a small pump. The shafting is 20 feet above the ground, near the roof of a granary. It is geared forward 6 to 1, and arranged so that the pump makes 1.011 strokes to each revolution of the wind wheel. The pump lifts 0.022 gallon per stroke a distance of about 40 feet. It has a cylinder 1.5 inches in diameter and a stroke of 8 inches. The supply pipe is on a well point. The brake pulley is 12 inches in diameter, the brake arm 3.75 feet long. The test was continued until the shafting failed. The mean baro-

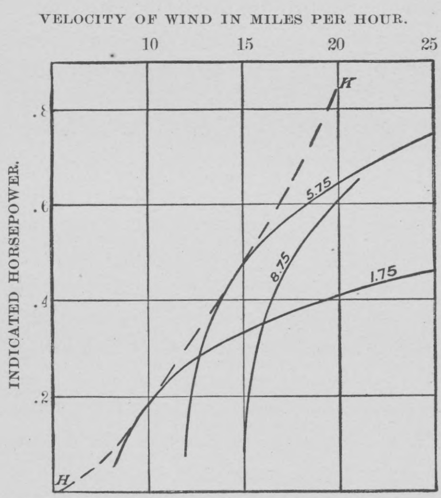


FIG. 38.—Diagram showing horsepower of mill No. 28—16-foot wooden Althouse. Curves marked 1.75, 5.75, and 8.75 show horsepower for brake loads of 1.75, 5.75, and 8.75 pounds, respectively; dotted curve *HK* shows maximum power.

metric pressure was 27.8 inches, the mean temperature 70° F. This mill had been in nearly constant use about five years. It replaced a 22.5-foot Halliday. The owner claims that the 16-foot steel mill does more work than the 22.5-foot Halliday wooden mill did. The results of the tests are as follows:

Results of tests of mill No. 29—16-foot Aermotor.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
1½	212	20	35	--------	--------	--------	0.13	0.23	--------	--------	--------
P+1½	487	11	30	41	--------	--------	0.17	0.44	0.636	--------	--------
P+2½	629	------	25	35	--------	--------	--------	0.48	0.714	--------	--------

Fig. 39 shows the number of revolutions of the wind wheel for three loads—212 foot-pounds, 487 foot-pounds, and 629 foot-pounds. Although these results are incomplete, on account of the failure of the shafting, they are complete up to a wind velocity of 15 miles an hour, and when studied in connection with the complete test of a mill of the same size and make (No. 44) it will be seen that this mill has about the same power for the same loads at any given wind velocity.

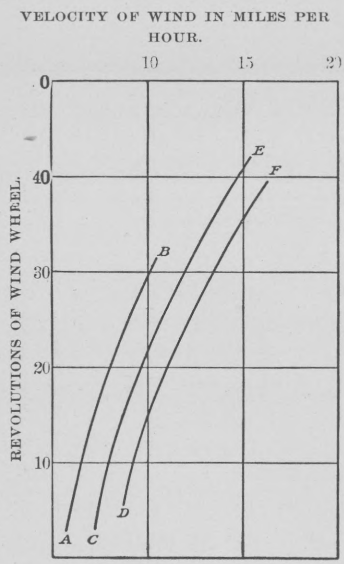


FIG. 39.—Diagram showing revolutions of wind wheel of mill No. 29—16-foot Aermotor. Curve *AB* is for a load of 212 foot-pounds; *CE* is for a load of 487 foot-pounds; *DF* is for a load of 629 foot-pounds.

Mill No. 30.—This is a 16-foot wooden power mill known as an Irrigator, used for lifting water. (For description see pp. 49–50, Part I.) Two brake loads (2 pounds and 16 pounds) were used on an arm 2.5 feet long. Curves showing the number of revolutions of the wind wheel per minute for these loads and the useful elevator load are reproduced in fig. 22, Part I; the horsepowers for these loads are shown in fig. 23, Part I.

Mill No. 31.—This is a 14-foot Elgin wooden power mill used to lift water with a rotary (Wonder) pump. It is described on pages 50 to 51, Part I.

Mill No. 34.—This is a 14-foot Junior Ideal steel power mill manufactured by the Stover Manufacturing Company, of Freeport, Illinois. The tower is of wood, 41 feet to the axis of the wheel. The wheel has

24 curved sails in eight sections, regulated on the centrifugal principle. Each sail is 49 by 18 by 8 inches, set at an angle of 29° to the plane of the wheel. This is a sectional vaneless mill. In place of a vane there is a counterpoise. It is geared forward 8 to 1. The mill is used for shelling and grinding corn and elevating. The brake pulley is on a line shaft 15 or 20 feet long. In a 12-mile wind the mill ground 12 pounds quite fine for a mile of wind, or at the rate of 144 pounds an hour. In an 18-mile wind it ground 26 pounds for a mile of wind, or at the rate of 468 pounds an hour. The grinder was made by the Baker Manufacturing Company, of Evansville, Wisconsin. The wind was unsteady, the temperature high—100° in the shade at noon. The results of the tests are as follows:

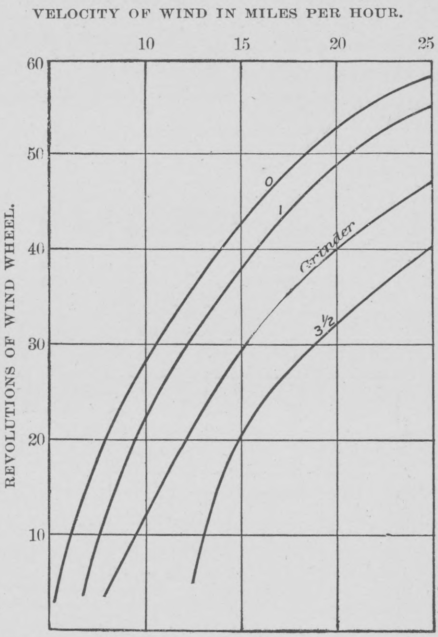


FIG. 40.—Diagram showing revolutions of wind wheel of mill No. 34—14-foot Junior Ideal. Curves marked 0, 1, 3½, and grinder are for brake loads of 0, 1, and 3.5 pounds, respectively, and for grinder load.

Results of tests of mill No. 34—14-foot steel Junior Ideal.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	20	34	44	53	58	--------	--------	--------	--------	--------
1	180	13	29	40	49	55	0.07	0.16	0.22	0.27	0.33
G.	G.	4	19	32	39	47	--------	--------	--------	--------	--------
3½	631	0	0	24	32	40	0	0	0.46	0.61	0.76

Fig. 40 shows the number of revolutions of the wind wheel per minute for brake loads of 0, 1, and 3.5 pounds, and for the grinder load. Fig. 41 shows the horsepower for brake loads of 1 and 3.5 pounds.

Mill No. 44.—This is a 16-foot Aermotor on a 40-foot steel tower. (See Pl. XV.) The working parts of the mill are like those shown in fig. 33; the foot gear is like that shown in fig. 34. The sail area is the same as that of mill No. 29, page 91. The power was measured with a wooden brake having an arm 4.67 feet long, on a 10-inch iron pulley on the foot gear. Five brake loads were used—0, 3, 5, 8, and 11 pounds, respectively. The shafting is geared forward 6 to 1.

The results of the tests are as follows:

Results of tests of mill No. 44—16-foot Aermotor.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	23	38	48.0	56	64.5	------	------	------	------	------
3	528	------	28	41.0	50	58.5	------	0.45	0.66	0.80	0.94
5	880	------	13	33.5	44	53.5	------	0.35	0.89	1.16	1.43
8	1,408	------	------	16.0	36	47.0	------	------	0.68	1.53	2.01
11	1,936	------	------	------	25	39.5	------	------	------	1.47	2.31

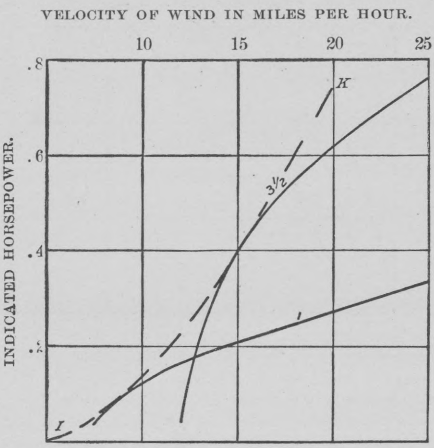


FIG. 41.—Diagram showing horsepower of mill No. 34—14-foot Junior Ideal. Curves marked 3½ and 1 show power for brake loads of 3.5 pounds and 1 pound, respectively; dotted curve *IK* shows maximum power.

Fig. 42 shows the number of revolutions per minute of the wind wheel for these brake loads. The number on each curve indicates the brake load for that curve. These curves are seen to closely resemble the corresponding curves for the 12-foot Aermotor (fig. 35). The 16-foot mill will be seen to start, with no load, in about a 4.5-mile wind—the same as the 12-foot Aermotor. Fig. 43 shows the horsepower of this mill for loads of 3, 5, 8, and 11 pounds, respectively. The curves for this mill closely resemble those of the 12-foot Aermotor. The curves of the latter were platted, but the diagram is not reproduced because of lack of space. It will be shown further on that these load curves are parabolas, and hence that the power increases as the square root of the wind velocity. It will be shown also that the curve of maximum power is a parabola, that the load for it increases nearly as the first power of the wind velocity, and that the speed of the wheel increases also as the first power of the wind velocity.

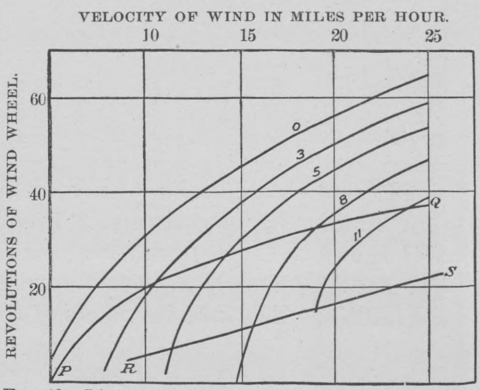
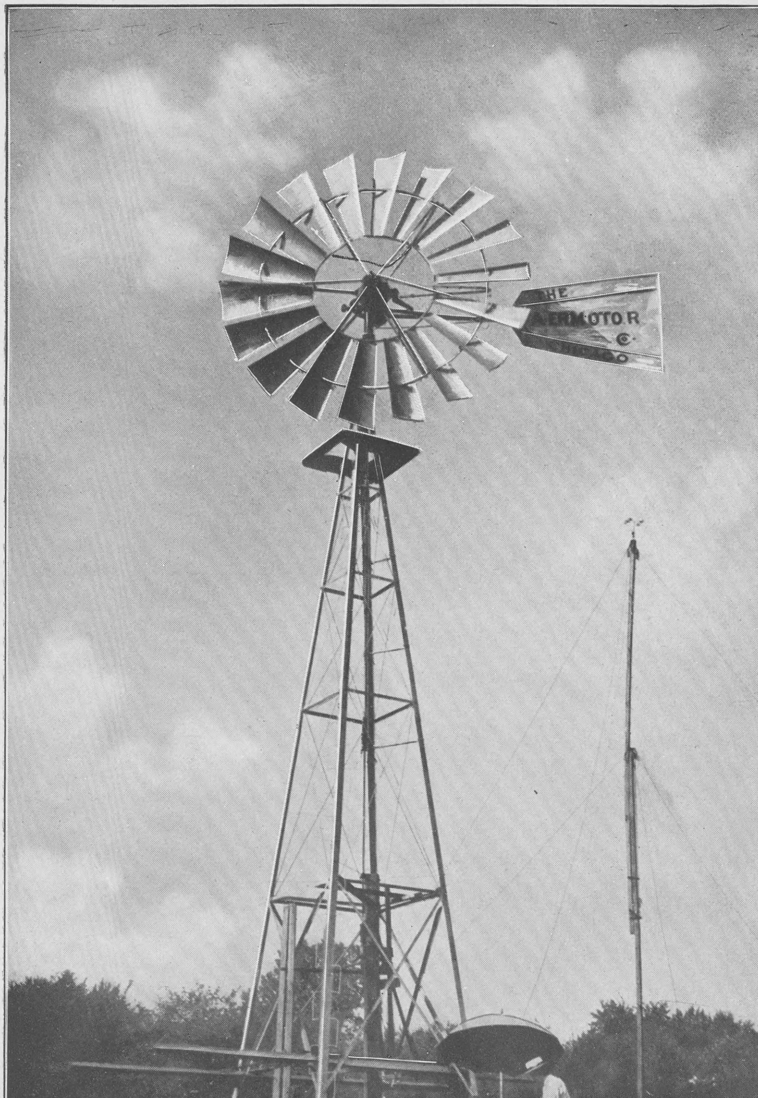


FIG. 42.—Diagram showing revolutions of wind wheel of mill No. 44—16-foot Aermotor. Curves marked 0, 3, 5, 8, and 11 are for brake loads of 0, 3 pounds, 5 pounds, 8 pounds, and 11 pounds, respectively; curve *PQ* is speed of wheel for maximum load; *RS* is load curve for maximum power.

Mill No. 49.—This is a



VIEW OF MILL NO. 44—16-FOOT AERMOTOR.

22.5-foot Halliday wooden power mill on a 43-foot wooden tower. The sail area is in two concentric rings, the outer ring having 144 sails, the inner ring 100 sails, each 43 by 4.5 by 3.5 inches, set at an angle of 25° to the plane of the wheel. The upper gearing has a ratio of 50 to 14, the lower gearing a ratio of 53 to 26, so that the horizontal shaft is geared forward 7.28 to 1. The brake pulley is 8 inches in diameter, the brake arm 4.75 feet long. The mean temperature was 82° F., the mean barometric pressure 28.7 inches. The mill is used for shelling and grinding corn. Four brake loads (0, 1.5, 5, and 9 pounds, respectively) were used, also the grinder load. The results of the tests are as follows:

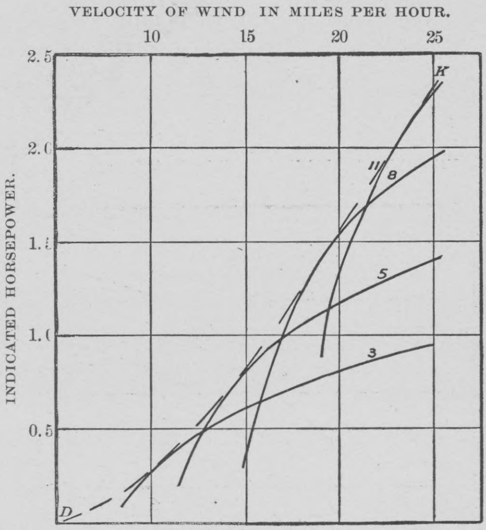


FIG. 43.—Diagram showing horsepower of mill No. 44—16-foot Aermotor. Curves marked 3, 5, 8, and 11 show power for brake loads of 3, 5, 8, and 11 pounds, respectively; dotted curve *DK* shows maximum power.

Results of tests of mill No. 49—22.5-foot wooden Halliday.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	11	20	25	30	32	......	......	......	......	......
1.5	326	6	16	22	26	30	0.059	0.163	0.217	0.257	0.296
5.0	1,087	......	11	18	22	26	......	0.342	0.593	0.724	0.856
G.	......	......	8	16	22	......	......	......	......	......	......
9.0	1,956	......	2	10	15	19	......	0.118	0.593	0.890	1.126

In a 13.5-mile wind the mill ground 20 pounds of chop quite fine in 4.5 minutes. Fig. 44 shows the number of revolutions per minute of the wind wheel for the five loads. This mill requires a 5.5-mile wind to start it without any load, and it makes only 32 revolutions in a 25-mile wind. This is about half as many as are made under the same conditions by the 16-foot mill No. 44. Since the circumference of the 22.5-foot mill is 1.4 times greater than that of the 16-foot mill, the circumference velocity of the 16-foot mill is 44 per cent greater than that of the 22.5-foot mill. The dotted curve, showing the speed of the wheel for the grinder load, will be seen to be a nearly straight line, showing a constantly increasing load with increase of wind velocity. Fig. 45 shows the horsepower for three loads, also the maximum horsepower. It will be seen that the power is small for so large a mill. The shafting of this mill is very heavy, and the grinder is run by a belt from the main shaft. The mill, although on a 43-foot tower, should be at least 20 feet higher. It will be seen to be a very poor mill.

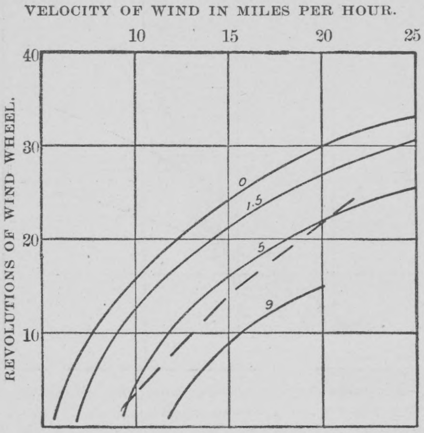


FIG. 44.—Diagram showing revolutions of wind wheel of mill No. 49—22.5-foot wooden Halliday. Curves marked 0, 1.5, 5, and 9 are for brake loads of 0, 1.5, 5, and 9 pounds, respectively; the dotted curve shows the speed of wheel for grinder load.

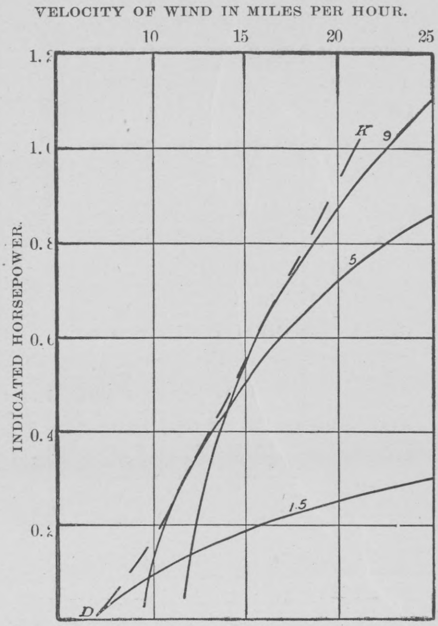


FIG. 45.—Diagram showing horsepower of mill No. 49—22.5-foot Halliday. Curves marked 9, 5, and 1.5 pounds show horsepower for brake loads of 9, 5, and 1.5 pounds, respectively; the dotted line *DK* shows maximum horsepower.

Mill No. 50.—This is a 12-foot Monitor wooden power mill on a 36-foot wooden tower. (See fig. 46.) It is a sectional mill and has 96 sails, each 44 by 4.25 by 1.75 inches, set at an angle of 34° to the plane of the wheel. The shaft is geared forward 3.66 to 1. The swivel gearing, which enables the mill to turn easily and keep full in the wind, is shown in fig. 47. The mill is used for shelling and grinding corn and pumping water. It is in very good condition, and the wind exposure is very good. The mill had been in use about three years. The mean temperature during the time of test was 83° F., the mean barometric pressure 28.6 inches.

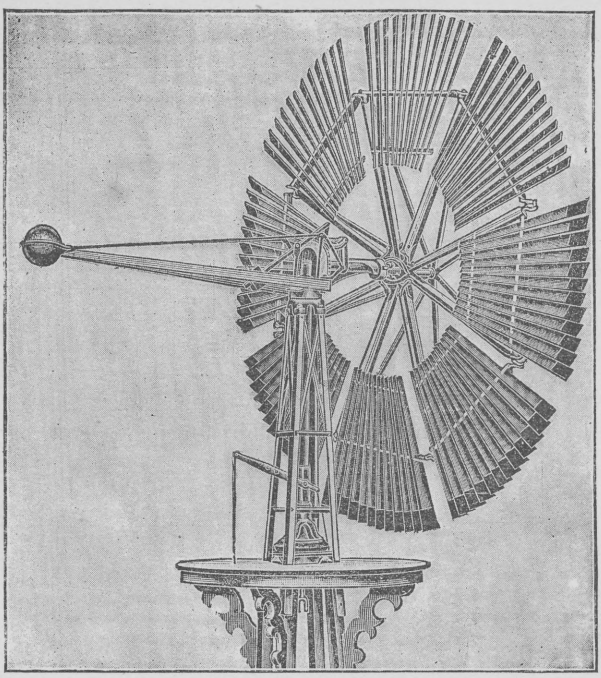


FIG. 46.—Mill No. 50—12-foot wooden Monitor.

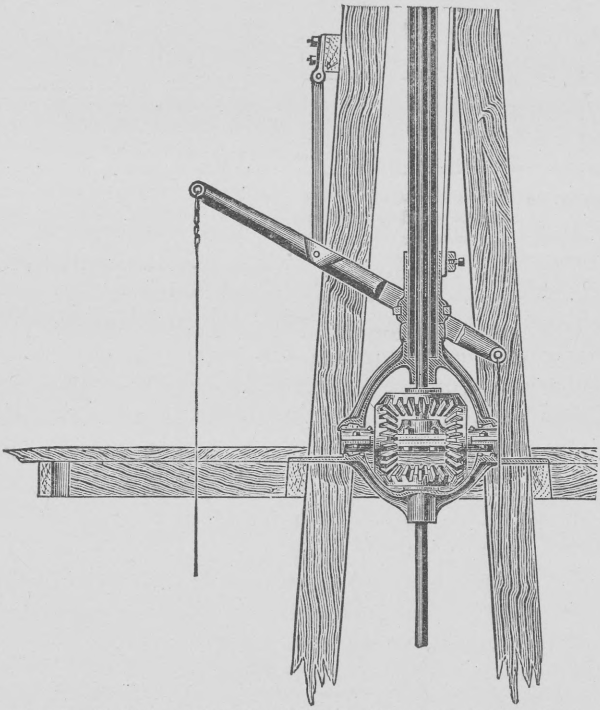


FIG. 47.—Swivel gearing of mill No. 50—12-foot wooden Monitor.

The results of the tests are as follows:

Results of tests of mill No. 50—12-foot wooden Monitor.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Lbs.	*Ft.-lbs.*										
0	0	16	33	44	54	64	------	------	------	------	------
1.5	120	------	25	35	43	52	------	0.091	0.127	0.156	0.189
2⅞	314	------	------	27	34	40	------	------	0.230	0.324	0.381
4.5	490	------	------	10	24	30	------	------	0.150	0.357	0.445

The revolutions of the wind wheel for three brake loads (0, 1.5, and 2.875 pounds) are shown in fig. 48. This figure also shows the number of revolutions for a 4.5-pound load, found by interpolation from the other results. This mill will be seen to require about a 6-mile wind to start it without any load and to make only 64 revolutions per minute in a 25-mile wind. The 12-foot Aermotor will start in a 4.5-mile wind and make 87 revolutions per minute in a 25-mile wind with no load. Fig. 49 shows the horsepower of this mill for the four loads; also the maximum horsepower.

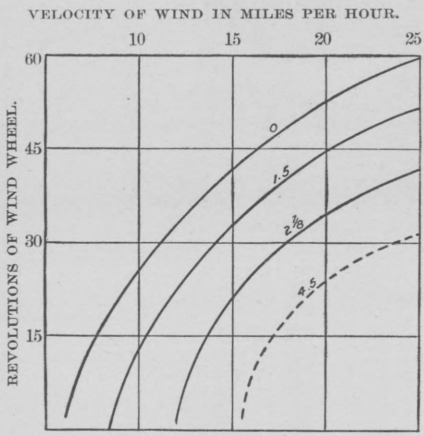


FIG. 48.—Diagram showing revolutions of wind wheel of mill No. 50—12-foot wooden Monitor. Curves marked 0, 1.5, 2⅞, 4.5 are for brake loads of 0, 1.5, 2⅞, and 4.5 pounds, respectively.

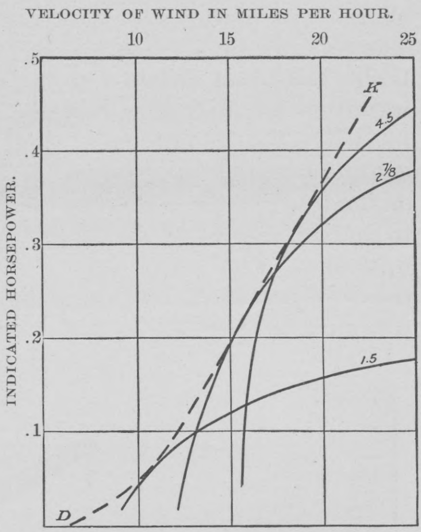


FIG. 49.—Diagram showing horsepower of mill No. 50—12-foot wooden Monitor. Curves marked 4.5, 2⅞, and 1.5 are for brake loads of 4.5, 2⅞, and 1.5 pounds, respectively; dotted curve *DK* shows maximum power.

Mill No. 52.—This is a 14-foot Challenge wooden power mill on a 45-foot wooden tower, manufactured by the Challenge Windmill Company, of Batavia, Illinois. (See fig. 50.) It is a sectional mill, and has two side wheels for keeping the main wheel in the wind. The wind wheel has 102 sails, each 51.5 by 5 by 1.75 inches, set at an angle of 39° to the plane of the wheel. The mill works a sheller, a grinder, and a pump. There are two horizontal shafts, one of which works the grinder and sheller, the other the pump. The shaft that works the pump is 12 feet long and 1.5 inches in diameter; it is geared forward 1.5 to 1. The shaft that works the grinder is 6 feet long and 1.5 inches in diameter; it is geared forward 15.25 to 1. The well is a drilled well, 192 feet deep. The lift was 180 feet, the discharge 0.25 quart per stroke. The water is pumped into a large box, and passes to watering troughs when needed. The pump has a counterweight which raises on the downstroke and assists in lifting the water on the upstroke. The mean temperature was 92° F., the mean barometric pressure 28.6 inches. The results of the tests are as follows:

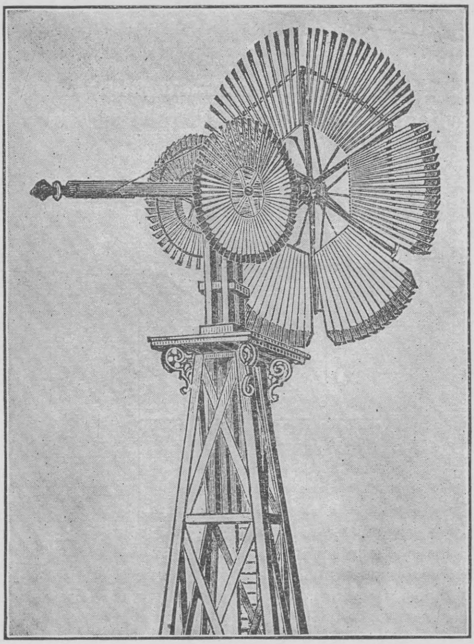


FIG. 50.—Mill No. 52—14-foot wooden Challenge.

Results of tests of mill No. 52—14-foot wooden Challenge.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Lbs.	*Ft.-lbs.*										
0	0	7	18	25	30						
Pump			14	22	27			0.059	0.093	0.115	
1	432			17	22				0.222	0.287	
2	864			8	16				0.210	0.420	

The revolutions of wind wheel per minute for loads of 0, 1, and 2 pounds are shown in fig. 51. For 0 load the pump shaft was running with the pump detached; the grinder shaft was not working. When pumping the grinder was not working. When the brake loads of 1 and 2 pounds were being used the pump shaft was not working. A curve was obtained giving the speed of the wind wheel for no brake load with the grinder shaft working and with the pump shaft not working. This curve nearly coincided with that for the pump load, showing that the friction of the grinder shaft was about equal to the pump load. With the pump shaft working, but not the pump, the mill will be seen to require a 7-mile wind to start it, and it makes only 30 revolutions in a 20-mile wind. Fig. 52 shows the horsepower of this mill.

This is a hard-running mill; there is too much friction. The side wheels do not respond to changes in the direction of the wind as quickly as does the vane or rudder in other mills. The wind exposure was very good and the mill was nearly new.

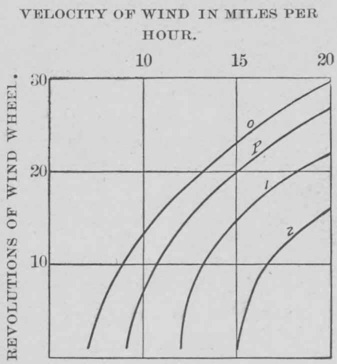


FIG. 51.—Diagram showing revolutions of wind wheel of mill No. 52—14-foot wooden Challenge. Curve marked 0 is for no brake load; curve *P* is for pump load; curves 1 and 2 are for brake loads of 1 and 2 pounds, respectively.

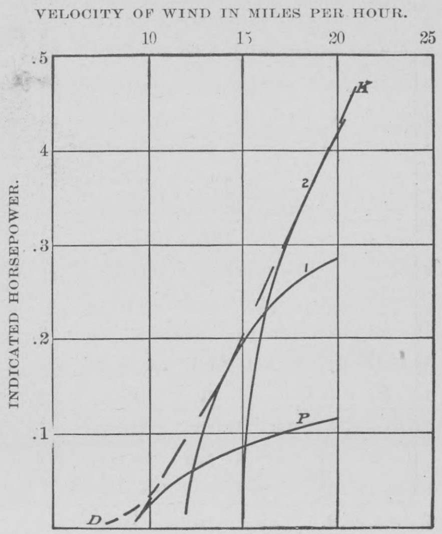


FIG. 52.—Diagram showing horsepower of mill No. 52—14-foot wooden Challenge. Curves marked 1 and 2 are for brake loads of 1 and 2 pounds, respectively; curve *P* is for pump load; dotted curve *DK* shows maximum power.

Mill No. 53.—This is a 12-foot Ideal power mill on a 33-foot wooden tower. The wind wheel has 21 curved sails, each 43.25 by 16.5 by 8.25 inches, set at an angle of 32° to the plane of the wheel. The horizontal shaft is geared forward 6.07 to 1. The mill had been in use about four years for shelling and grinding corn. Three brake loads were used in the test—0, 1.5, and 2.5 pounds. The mean temperature during the tests was 92° F., the mean barometric pressure 28.7 inches. The results of the tests are as follows:

Results of tests of mill No. 53—12-foot Ideal.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower of mill at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	25	40	51	60	68	-------	-------	-------	-------	-------
1.5	272	------	29	41	51	60	-------	0.239	0.338	0.420	0.500
2.5	455	------	------	32	44	54	-------	-------	0.440	0.606	0.745

Fig. 53 shows the number of revolutions per minute of the wind wheel for the three brake loads. The mill will be seen to start in about a 5-mile wind and to make 69 revolutions a minute in a 25-mile wind with no load. Fig. 54 shows the horsepower for the several loads.

Mill No. 54.—This is a 12-foot Aermotor like No. 27, on a 47-foot tower. The 12-foot Aermotor No. 27 was found to be so much greater in power and speed than other 12-foot mills tested that we thought

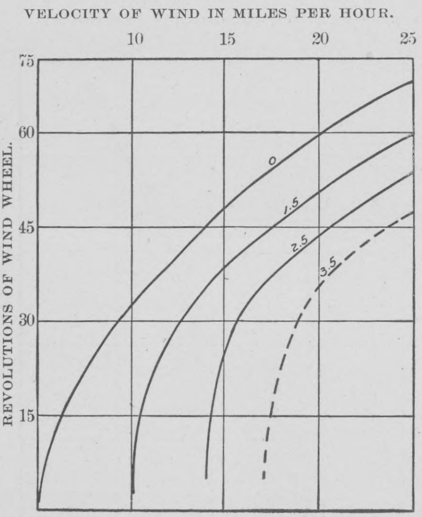


FIG. 53.—Diagram showing revolutions of wind wheel of mill No. 53—12-foot Ideal. Curves marked 0, 1.5, 2.5, and 3.5 are for brake loads of 0, 1.5, 2.5, and 3.5 pounds, respectively.

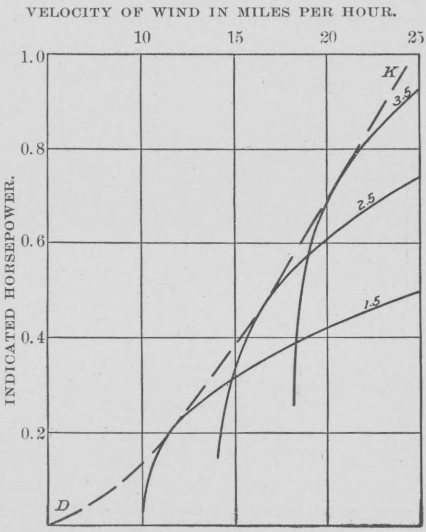


FIG. 54.—Diagram showing horsepower of mill No. 53—12-foot Ideal. Curves marked 3.5, 2.5, and 1.5 are for brake loads of 3.5, 2.5, and 1.5 pounds, respectively; dotted curve *DK* shows maximum power.

it wise to test another of the same make and size under somewhat different conditions. No. 54 had been in use about two years. Two brake loads were used—0 and 297 foot-pounds per revolution of wind wheel. The mean temperature during the test was 92° F., the mean barometric pressure 29.2 inches. The results of the tests are as follows:

Results of tests of mill No. 54—12-foot Aermotor.

Load on brake.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	31	49	63	75	87	--------	--------	--------	--------	--------
1.75	297	------	38	52	63	75	--------	0.34	0.46	0.57	0.68

It will be seen that the results of the tests of this mill apparently agree closely with those of No. 27, page 86. The agreement, however, is not so close as it appears, since the temperature for No. 54 is much higher. It is, however, about the same as the temperature for other mills, so that we can still use the results found for mill No. 27 in comparing its power and speed with those of other mills.

COMPARISON OF POWER MILLS.

Comparison of 12-foot Ideal (No. 53) with 14-foot Ideal (No. 34).—It must be remembered that in this and in all other comparisons no correction is made for difference in temperature and barometric pressure. The speeds for no load and the maximum horsepowers for these mills are as follows:

Comparison of results for 12-foot Ideal and 14-foot Ideal.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Maximum horsepower at given wind velocities (per hour).				
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
12-foot Ideal	25	40	51	60	68	0.06	0.23	0.44	0.70	------
14-foot Ideal	20	34	44	53	58	0.06	0.22	0.46	0.74	------
Ratio of circumference velocities ($\frac{12}{14}$)	1.07	1.00	0.99	0.97	1.00	------	------	------	------	------

It will be seen that the useful power of the 14-foot mill is very little more than that of the 12-foot mill, and that the circumference velocities are nearly the same for no load, where no horizontal shaft is being turned. In the case of the 12-foot mill the brake was on the foot gear and there was no horizontal shaft to turn, but in the case of the 14-foot mill the brake pulley was on a shaft 15 or 20 feet long. We believe that if the brake pulley had been on the foot gear and the line shaft thrown out of gear, so as to eliminate shaft friction, the mill would have shown at least 10 per cent more power. The tower obstructs the wheel somewhat and reduces the power.

Comparison of 12-foot Aermotor (No. 27) with 14-foot Ideal (No. 34).—The speeds for no load and the maximum horsepowers for these mills are as follows:

Comparison of results for 12-foot Aermotor and 14-foot Ideal.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Maximum horsepower at given wind velocities (per hour).			
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.
12-foot Aermotor	30	49	63	75	87	0.09	0.33	0.66	1.05
14-foot Ideal	20	34	44	53	58	0.06	0.22	0.46	0.74
Ratio of circumference velocities ($\frac{12}{14}$)	1.29	1.23	1.22	1.21	1.28	------	------	------	------

It will be seen that the number of revolutions per minute of the 12-foot mill is 50 per cent greater than for the 14-foot mill. This is true for the lower as well as for the higher velocities, where the governing of the mill does not enter to reduce the speed. It will be seen also that the 12-foot mill is producing from 42 to 50 per cent more horsepower than the 14-foot mill. The temperature was 49° higher and the pressure 0.6 inch lower when the 14-foot mill was tested than when the 12-foot mill was tested. The effect is to lessen the difference between the power and speeds of the mills.

Comparison of 12-foot Aermotor (No. 27) with 16-foot Aermotor (No. 44).—Attention has already been drawn to the similarity between the speed curves of these mills (figs. 35 and 42) and between the power curves. (The power curves for mill No. 44 are shown in fig. 43; those for mill No. 27 were platted, but are not published because of lack of space.) If we compare the number of revolutions per minute for no load, we shall see that they are to each other nearly inversely as the diameter, or that the circumference velocities of the two mills are the same in all wind velocities. We may compare the brake horsepower and the speed as follows:

Comparison of results for 12-foot Aermotor and 16-foot Aermotor.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Maximum horsepower at given wind velocities (per hour).		
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	10 miles.	15 miles.	20 miles.
12-foot Aermotor	30	49	63	75	87.0	0.21	0.58	1.05
16-foot Aermotor	23	38	48	56	64.5	0.29	0.82	1.55
Ratio of circumference velocities ($\frac{16}{12}$)	1.02	1.03	1.02	0.99	0.99	1.38	1.41	1.48

From this it will be seen that the power of the 16-foot Aermotor is about 1.22 times that of the 12-foot. The ratio of the squares of the diameters is 1.78; the ratio of the diameters 1.33. It will be seen that the power does not increase as the squares of the diameters, as is often stated; it increases faster than as the diameters, but more nearly as the diameters than as the squares of the diameters.

Comparison of 16-foot Althouse wooden mill (No. 28) with 16-foot Aermotor (No. 44).—From the following table it will be seen that the wind wheel of No. 44 is revolving from 56 to 77 per cent faster than the wind wheel of No. 28. The latter, however, has to overcome the friction of 10 or 12 feet of line shafting. It will be seen that No. 44 is yielding from 70 to 167 per cent more power than No. 28. The superiority of the steel mill over the wooden mill is very evident in this case.

Comparison of results for 16-foot Althouse and 16-foot Aermotor.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Maximum horsepower at given wind velocities (per hour).			
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.
16-foot Althouse	13	23	30	36	40.0	0.06	0.29	0.52	------
16-foot Aermotor	23	38	48	56	64.5	0.16	0.48	0.93	1.55
Ratio of circumference velocities $\left(\frac{\text{steel}}{\text{wood}}\right)$	1.77	1.65	1.60	1.55	1.61	2.67	1.65	1.78	------

Comparison of 22.5-foot Halliday wooden mill (No. 49) with 16-foot Aermotor (No. 44).—From the following table it will be seen that the steel mill makes about two revolutions to one revolution of the wooden mill, and that its power is from 41 to 167 per cent greater.

Comparison of results for 22.5-foot Halliday and 16-foot Aermotor.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).				Maximum horsepower at given wind velocities (per hour).			
	8 miles.	12 miles.	16 miles.	20 miles.	8 miles.	12 miles.	16 miles.	20 miles.
22.5-foot Halliday	11	20	25	30	0.06	0.34	0.62	0.88
16-foot Aermotor	23	38	48	56	0.16	0.48	0.93	1.55
Ratio of circumference velocities $\left(\frac{16}{22.5}\right)$	1.48	1.35	1.36	1.32	2.67	1.41	1.50	1.76

Comparison of 12-foot Aermotor (No. 27) with 22.5-foot Halliday wooden mill (No. 49).—Comparing the power of these mills, we have the following:

Comparison of results for 12-foot Aermotor and 22.5-foot Halliday.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).				Maximum horsepower at given wind velocities (per hour).			
	8 miles.	12 miles.	16 miles.	20 miles.	8 miles.	12 miles.	16 miles.	20 miles.
12-foot Aermotor	30	49	63	75	0.09	0.33	0.66	1.05
22.5-foot Halliday	11	20	25	30	0.06	0.32	0.63	0.94
Ratio of circumference velocities $\left(\frac{12}{22.5}\right)$	1.46	1.31	1.34	1.32	1.50	1.03	1.05	1.12

It will be seen that this 22.5-foot wooden mill does not furnish as much power as a good 12-foot steel mill.

Comparison of wooden power mills.—Of the mills in the following table the 12-foot has the least friction; the tower being in front of the windmill obstructs the wheel and reduces the power. The 14-foot mill probably has more friction than the others. The 16-foot Irrigator has too few sails; with more sails the power could probably be increased 75 per cent or more.

Comparison of results of tests of wooden power mills.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).			
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.
12-foot Monitor (No. 50)	16	33	44	54	64	0.02	0.10	0.23	0.38
14-foot Challenge (No. 52)	7	18	25	30	......	0.01	0.10	0.25	0.42
16-foot Althouse (No. 28)	13	23	30	36	40	0.06	0.29	0.52	0.84
16-foot Irrigator (No. 30)	12	25	32	41	44	0.02	0.16	0.30	0.44
22.5-foot Halliday (No. 49)	11	20	25	30	......	0.06	0.32	0.63	0.94

It will be seen that the 16-foot mill (No. 28) is furnishing from 2.2 to 2.9 times more useful power than the 12-foot mill (No. 50). It will also be seen that the power of this 16-foot mill compared with that of the 12-foot mill increases faster than as the squares of the diameters, while the power of the 22.5-foot mill compared with that of the 12-foot mill does not increase as fast as the squares of the diameters, and the power of the 22.5-foot mill compared with that of the 16-foot mill does not increase as fast as the first power of the diameters.

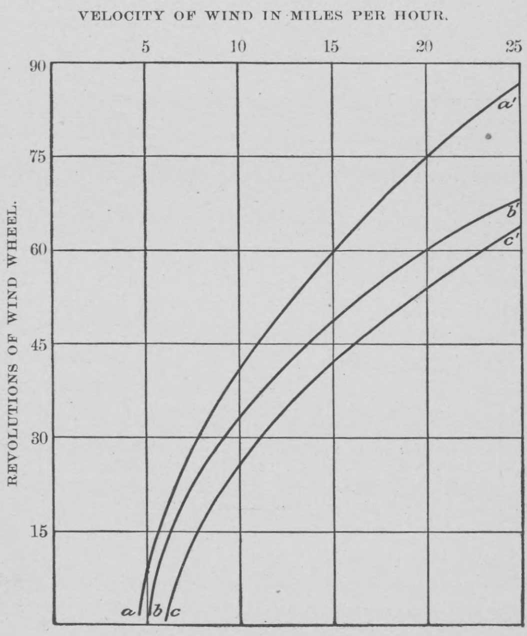


FIG. 55.—Comparative diagram of revolutions of wind wheels of mills Nos. 50, 53, and 27. Curve *aa'* is for 12-foot Aermotor; *bb'* is for 12-foot Ideal; *cc'* is for 12-foot Monitor.

Comparison of 12-foot Monitor wooden mill (No. 50) with 12-foot Aermotor (No. 27) and with 12-foot Ideal (No. 53).—Fig. 55 shows the speed, in revolutions, of the wind wheels of these mills for no useful load. The friction is small in each case. The Monitor has a swivel gearing, and the Ideal has a ball gearing to carry the weight of the shaft, both of which reduce the friction. It is fair to say that the friction load of the Aermotor is at least as great as that of the other mills. It will be seen that the speed of the Ideal is noticeably greater than that of the Monitor; and that the speed of the Aermotor is much greater than that of the Ideal, especially for high wind velocities. This is the reason the Aermotor is so much more powerful than other mills. It revolves much faster, and the power is directly proportional to the speed. But why is its speed greater for the same load?

Comparison of results for 12-foot Monitor, 12-foot Ideal, and 12-foot Aermotor.

Mill.	Load per revolution of wind wheel.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
	Ft.-lbs.										
12-foot Monitor	0	16	33	44	54	64	------	------	------	------	------
	120	------	25	35	43	52	------	0.091	0.127	0.156	0.189
	314	------	------	27	34	40	------	------	0.230	0.324	0.381
12-foot Ideal	0	25	40	51	60	68	------	------	------	------	------
	272	------	49	41	51	60	------	0.239	0.338	0.420	0.500
	455	------	------	32	44	54	------	------	0.440	0.606	0.745
12-foot Aermotor	0	30	29	63	75	87	------	------	------	------	------
	222	16	43	57	70	81	0.089	0.285	0.386	0.458	0.523
	444	------	23	48	65	77	------	0.303	0.653	0.890	1.020
	666	------	------	12	50	72	------	------	0.234	1.028	1.451

The dimensions of the principal parts of the wind wheels of these mills and the mean temperature and pressure when the tests were made are as follows:

Dimensions of principal parts of mills Nos. 50, 53, and 27.

Mill.	Number of sails.	Dimensions of sails.	Angle of sails.	Gearing.	Mean temperature.	Mean barometric pressure.
		Inches.	°		° *F.*	*Inches.*
12-foot Monitor (No. 50)	96	44 x 4¼x1¾	34	3.66 : 1	83	28.6
12-foot Ideal (No. 53)	21	43¼x16½x8¼	32	6.07 : 1	92	28.7
12-foot Aermotor (No. 27)	18	44 x18¾x7¾	31	6.00 : 1	46	28.9

The temperature when the 12-foot Aermotor was tested was much lower than when the other two mills were tested, but, as already stated, the temperature when Aermotor No. 54 was tested was 92° F., and it showed a speed and power about the same as Aermotor No. 27; so we may leave this difference in temperature out of account.

It will be seen that the Monitor is not geared forward as much as the other two, but this does not affect the speed for no load. The sail angle is about the same for all, also the length of sail; but the number of sails and the width are quite different. The Aermotor has few sails, but of large size; the Ideal has more and somewhat smaller sails; the Monitor has many small sails, and its tower is located in front of the wind wheel. Its sails are plane, instead of curved, all of which tends to decrease its power.

Fig. 56 shows the curves of maximum horsepower. It will be seen that the difference between the horsepower of the Aermotor and that of the Ideal is about the same as the difference in their speeds for the same wind velocity, but the difference between the power of the Monitor and that of the Ideal is much greater than the corresponding difference in their speeds. The wooden mill, therefore, not only has a less speed at a given wind velocity than the steel mill, but it carries a proportionately less load. For example, in a 20-mile wind a load of 120 foot-pounds per revolution reduces the speed of the Monitor from 54 to 43 (or 11) revolutions per minute, while in the case of the Aermotor a load of 220 foot-pounds (about 80 per cent greater) reduces the speed from 75 to 70 (only 5) revolutions per minute. In the case of the Ideal a load of 272 foot-pounds per revolution (2.3 times the load of the Monitor) reduces the speed from 60 to 51 (or 9) revolutions per minute.

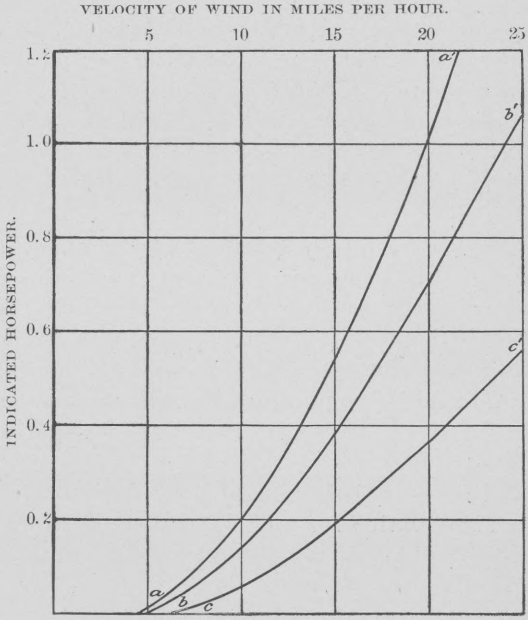


FIG. 56.—Comparative diagram of horsepower of mills Nos. 50, 53, and 27. Curve *aa'* is for 12-foot Aermotor; *bb'* is for 12-foot Ideal; *cc'* is for 12-foot wooden Monitor.

COMPARISON OF PUMPING MILLS WITH POWER MILLS.

Comparison of 12-foot pumping mill (No. 3) with 12-foot power mill (No. 27).—The load per stroke of No. 3 (see page 30, Part I) is 415.3 foot-pounds. The wind wheel makes 3.3 revolutions to 1 stroke of the pump, so that the load per revolution of wind wheel is 124.5 foot-pounds. This is less than the smallest load used in testing No. 27, viz, 222 foot-pounds per revolution. A diagram was platted showing the useful work, in horsepower, of these mills for these loads. The curve for the pumping mill was seen to start with a little less wind velocity than that of the power mill, indicating a somewhat less total load.

Comparing the ordinates of these curves for different wind velocities, the following ratios were obtained, which give, approximately, the pump efficiency, no allowance being made for difference in temperature and pressure:

8	12	16	20	25	30
0.60	0.53	0.54	0.54	0.58	0.58

The mean of these ratios is 0.56. If the useful load of the pumping mill had been somewhat greater, so that the mills would have started at the same wind velocity, the ratio, or pump efficiency, would be about 60 per cent, which is about what might be expected of this pump under this lift. The ratio of the useful loads is $125 \div 222 = 0.57$. This ratio would probably be about 0.60 if the loads were such that the mills would start at the same wind velocity.

Comparison of 16-foot pumping Aermotor (No. 9) with 16-foot power Aermotor (No. 44).—The useful load of No. 9 (see pages 36 to 37, Part I) is 1,013 foot-pounds per stroke of pump, or 304 foot-pounds per revolution of wind wheel. The smallest useful load of No. 44 is 528 foot-pounds per revolution of wind wheel. A diagram was platted showing the useful horsepower of these mills for these loads. For this particular load (1,013 foot-pounds) the pumping mill was seen to start at a somewhat less wind velocity than the power mill, indicating that the total load of the pumping mill was somewhat less than that of the power mill. The ratio of any two of the ordinates gave, approximately, the pump efficiency for that wind velocity, the difference in temperature and pressure being neglected.

These ratios for four velocities are as follows:

12	16	20	25
0.72	0.67	0.69	0.63

If the pump load had been somewhat greater—such that the mills would start at the same wind velocity—the mean ratio would be about 70 per cent. This, again, is about what is expected for the efficiency of this pump, which is somewhat better than mill No. 3 and has a higher lift. The ratio of the useful loads of these mills is $304 \div 528 = 0.57$. This ratio would probably be about 60 per cent if the mills started at the same wind velocity.

It is interesting to compare the performance of these mills still further. The speeds of the wheels and the horsepowers are as follows:

Comparison of results for 16-foot pumping Aermotor and 16-foot power Aermotor.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).				Horsepower at given wind velocities (per hour).				Load per revolution of wind wheel.
	12 miles.	16 miles.	20 miles.	25 miles.	12 miles.	16 miles.	20 miles.	25 miles.	*Ft.-lbs.*
16-foot pumping mill (No. 9)	31	42	52	59	0.325	0.433	0.548	0.601	0.304
16-foot power mill (No. 44)	28	41	50	58	0.45	0.65	0.80	0.95	0.528
Ratio of pump power to mill power	------	------	------	------	0.72	0.67	0.69	0.63	0.58

It will be seen that the wind wheel of the pumping mill is making from one to two more revolutions per minute than that of the power mill.

Comparison of 22.5-foot pumping mill (No. 36) with 22.5-foot power mill (No. 49).—In this comparison we will use the curve of 5 pounds, or 1,087 foot-pounds, per revolution of wind wheel as the speed for this load, corresponding more nearly with that for the pump load than any other. The speeds of the mills and the horsepowers are as follows:

Comparison of results for 22.5-foot pumping mill and 22.5-foot power mill.

Mill.	Number of revolutions of wind wheel per minute at given wind velocities (per hour).				Horsepower at given wind velocities (per hour).				Load per revolution of wind wheel.
	12 miles.	16 miles.	20 miles.	25 miles.	12 miles.	16 miles.	20 miles.	25 miles.	*Ft.-lbs.*
22.5-foot pumping mill (No. 36)	12	17	20	24	0.090	0.124	0.150	0.182	0.248
22.5-foot power mill (No. 49)	11	18	22	26	0.342	0.593	0.724	0.856	1.087
Ratio of pump power to mill power	------	------	------	------	0.26	0.20	0.20	0.22	0.23

The efficiency of the pump is, therefore, not more than 22 per cent. The ratio of useful loads is 22 per cent. (For description of pumping mill No. 36, see pages 52 to 53, Part I.)

EFFECT OF TENSION OF SPRING ON SPEED AND HORSEPOWER OF MILL.

The effect of tightening the spring which holds the wind wheel of mill No. 18 in the wind has been shown on page 44, Part I. The effect of a reduction in the tension of the spring of the 16-foot power mill (No. 44) is shown in fig. 57. The curve aa' is for no load and the spring new and stiff. The curve aa'' is for the same load (none) and spring after the mill had been out of use about eight months. It will be seen that these curves coincide up to a velocity of about 10 miles an hour, after which they separate rapidly. In a 25-mile wind the number of revolutions of the wind wheel per minute has been reduced from 64.5 to 54 by the decrease in the tension of the spring. The curve bb' is for a 3-pound brake load with relaxed spring. It will be seen to be nearly parallel to the curve aa'', showing that the effect of the load when the spring is relaxed is similar to that when it is taut. We see how important a factor tension of spring is on the power of a mill. It also shows that if a spring is to be used in place of a weight there should be some easy way to change its tension.

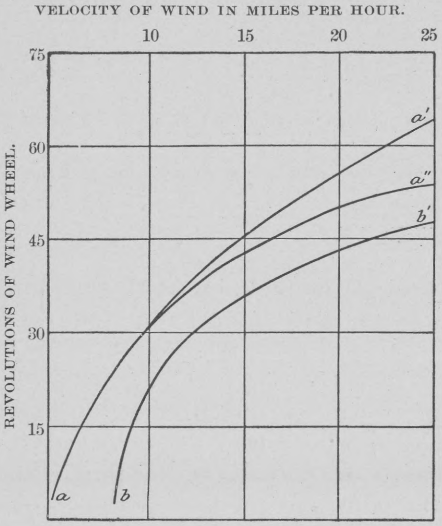


FIG. 57.—Diagram showing effect of tension of spring of mill No. 44—16-foot Aermotor. Curve aa' is for no load, spring new and stiff; aa'' is for no load, spring relaxed, mill having been out of use eight months; bb' is for 3-pound brake load with relaxed spring.

MATHEMATICAL DISCUSSION OF TESTS OF TWO AERMOTORS.

In this discussion the wind velocities are those found by the use of the Robinson cup anemometer. A comparison of these velocities with true wind velocities will be given later. The Aermotors are selected for this discussion because their power is greater than that of any other form of mill that we have tested, and because their speed and power curves are derived from a greater number of observations than those of any other mill.

Discussion of tests of 12-foot Aermotor (No. 27).—The curves showing the number of revolutions of wind wheel (called speed curves) of this mill for four brake loads are given on page 88—fig. 35. Each of these curves is seen to resemble a parabola the axis of which is the x coordinate axis on which the wind velocities are marked. Each of these has the form $y^2 = a + bx$, in which x is the wind velocity in miles per hour, y the speed of wind wheel in revolutions per minute, and a and b constants. For the curve of no load (0) we have $y = 50$ when $x = 12$, and $y = 75$ when $x = 20$. Hence we have

$$50^2 = a + 12b, \text{ and}$$
$$75^2 = a + 20b.$$

Solving these, for a and b we have $a = -2{,}187$ and $b = 391$; and the equation of the curve is

$$y^2 = -2{,}187 + 391x. \tag{1}$$

For the speed curve of 2 pounds we see that $y = 43$ when $x = 12$, and that $y = 70$ when $x = 20$. Hence we have

$$43^2 = a + 12b, \text{ and}$$
$$70^2 = a + 20b.$$

Solving these, we have $a = -2{,}728$ and $b = 381$; and we have the equation of this 2-pound curve

$$y^2 = -2{,}728 + 381x. \tag{2}$$

Proceeding in a similar way, we have for the equation of the 4-pound curve

$$y^2 = -4{,}384 + 424x. \tag{3}$$

For the equation of the 6-pound curve we have

$$y^2 = -9{,}400 + 595x. \tag{4}$$

The speed as determined by measurement and as found from these equations for several wind velocities is shown the following table.

The starting velocities are found by making $y = 0$ and solving for x in equations 1 to 4.

Table showing revolutions per minute of 12-foot Aermotor (No. 27) under different loads and at different wind velocities.

Wind velocity per hour.	No load.		2-pound load.		4-pound load.		6-pound load.	
	Measured.	Computed.	Measured.	Computed.	Measured.	Computed.	Measured.	Computed.
	Rev.	*Rev.*	*Rev.*	*Rev.*	*Rev.*	*Rev.*	*Rev.*	*Rev.*
8 miles	30	30	16	18	......	......	......	......
12 miles	49	50	43	43	23	27	......	......
16 miles	63	64	57	58	48	49	12	10
20 miles	75	75	70	70	65	64	50	50
25 miles	87	87	81	82	77	78	72	74
Starting velocity	4.5	5.6	7.0	7.1	10.2	10.3	15.3	15.8

If the origin of coordinates for equation 1 be moved to the point where the curve crosses the axis of x, the equation will then be of the form $y^2 = 391x'$, from which we have $y = \sqrt{391x'}$; that is, the speed for a constant load increases as the square root of the wind velocity.

The close agreement between the measured and computed speeds, especially for the curve of no load, is noticeable. The measured and computed starting velocities differ somewhat. This was expected, since it is difficult to get the starting velocities from observation.

Hereafter in this discussion the computed instead of the observed speeds and starting velocities will be used. It must be remembered, however, that these are not what may be called theoretical results. They are obtained from measurements, not from theory, and are the adjusted values of the observed quantities.

The power curves for this mill for three brake loads were platted, but are not published because of lack of space. The curves are parabolas with their axes horizontal. This follows at once from the fact that the corresponding speed curves are parabolas. The power is proportional to the product of the load and speed. When the load is constant, as it is for one of these speed curves, the power varies as the speed, and hence the load curves are parabolas.

The equation of any one of the curves—as, for example, the 2-pound curve—may be found as follows: The formula for horsepower is H. P. $= 2\pi RuL \div 33{,}000$, $R = 35.5 \div 12$ and $L = 2$. Hence H. P. $= 2 \times \overline{22 \div 7} \times 6 \times 35.5 \times 2 \times u \div \overline{12 \times 33{,}000} = 0.0067u = Ku$ where $K = 0.0067$.

In the speed equations u is what we have called y, and $y = -2{,}728 + 381x$. Hence—

$$\text{H. P.} = Ky = K\sqrt{-2{,}728 + 381x}, \text{ and}$$

$$(\text{H. P.})^2 = K^2(-2{,}728 + 381x) = -0.1225 + 0.017x. \qquad (5)$$

In the diagram of power curves, platted but not reproduced here, the curve of maximum power was found to resemble a parabola the axis of which was vertical with its vertex on the y coordinate axis below the origin. The form of its equation is $x^2 = a + by$, x being the wind velocity, in miles per hour, y the horsepower, and a and b constants. For $x = 5$, $y = 0$, and for $x = 20$, $y = 1.05$. Substituting these values in the above equation we have: $25 = a$, and $400 = a + 1.05b$. From these we have: $a = 25$, $b = 357$, and the equation of the maximum power curve is—

$$x^2 = 25 + 357y. \qquad (6)$$

For $x = 5$, 10, 15, 20, and 25, y has the values 0, 0.21, 0.56, 1.05, and 1.69, which agree closely with those taken from the curve.

For the mill to yield the greatest amount of power possible the load should increase as the wind velocity increases. In an 8.5-mile wind a 2-pound load gives the maximum power; in a 14-mile wind a 4-pound load gives the maximum power, and in a 21-mile wind a 6-pound load gives the maximum power.

We wish to determine how the load and speed of the mill vary with the wind velocity for the curve of maximum power. The load curves were found to be tangent to the curve of maximum power for loads and velocities about as follows: The 0 curve is tangent at $x=5$, the 2-pound curve at $x=8.5$, the 4-pound curve at $x=21$. For a constant increment of 2 pounds in the load the increment of wind velocity changed from 3.5 miles to 7 miles. Hence the velocity increases faster than the loading. For each of these four points on the curve the load and horsepower are known. Hence we can find the number of revolutions from the equation—

$$\text{H. P.} = 2 \times \pi \times R \times 6 \times 4 \times L \div 33{,}000. \tag{7}$$

The wind velocities, loads, powers, and speeds for these four points of tangency are as follows:

Data regarding points of tangency of power curves with curves of maximum power of Aermotor No. 27.

Wind velocity per hour.	Load.	Horsepower.	Revolutions per minute.
	Pounds.		
5 miles	0	0	0
8.5 miles	2	0.13	19
14 miles	4	0.50	38
21 miles	6	1.15	57

The speeds, in revolutions, as here given are platted in fig. 35, giving the curve PQ, which is the speed curve for maximum power. The proper load for maximum power can now be found for any wind velocity from equation 7, the speed being taken from this speed curve. The ratio of the speed at maximum load to the speed at 0 load, for the wind velocities 10, 15, and 20 miles an hour, is 0.63, 0.70, and 0.74, respectively, showing quite an increase. The following table gives additional information in regard to speed and load for the curve of maximum power:

Data regarding speed and load for curve of maximum power of Aermotor No. 27.

Wind velocity per hour.	Load per revolution of wind wheel.	Revolutions per minute.	L — L′.	S — S′.	LS.	LS — L′S′.	Δ^2.
	Pounds.						
5 miles	0	0	--------	--------	------	--------	--------
10 miles	2.1	25	2.1	25	52.5	52.5	--------
15 miles	4.0	41	1.9	16	160.4	107.9	55.4
20 miles	5.9	55	1.9	14	324.5	164.1	56.2

The fourth column gives the differences between the successive loads, or the increments of loading. These are seen to decrease somewhat, showing that the load does not increase quite as fast as the wind velocity. The fifth column gives the differences between the successive speeds, and shows that the speed does not increase quite as fast as the wind velocity. The sixth column gives the products of the loads and speeds, which is proportional to the horsepower. The seventh column gives the increments of horsepower, the eighth column the difference between the figures in the seventh column. These, being nearly constant, show that the curve of maximum power is of the second degree.

The following table contains additional interesting information in regard to the speed of this mill:

Data in regard to speed of mill No. 27—12-foot Aermotor.

Wind velocity per hour.	Revolutions per minute, no load.	Circumference velocity, in miles, no load.	Ratio of circumference velocity to wind velocity, no load.	Revolutions per minute at maximum load.	Ratio of speed at maximum load to speed at no load.
8 miles	30	12.9	1.61	17	0.57
12 miles	49	21.0	1.75	32	0.65
16 miles	63	27.0	1.70	44	0.70
20 miles	75	32.1	1.60	54	0.72
25 miles	87	37.3	1.50		

The results obtained from this 12-foot mill may be stated as follows, in terms of cup anemometer velocities:

(1) The speed of the wheel for a constant load varies as the square root of the wind velocity.

(2) The speed of the wheel for maximum load increases slightly faster than the first power of the wind velocity.

(3) The power of the mill for a constant load varies as the square root of the wind velocity.

(4) The maximum power of the mill varies as the square of the wind velocity.

(5) The load for maximum power does not increase quite as fast as the wind velocity.

(6) The ratio of speed for maximum load to the speed for no load increases somewhat with the wind velocity.

Discussion of tests of 16-foot Aermotor No. 44.—The speed curves for this mill are shown in fig. 42. They are seen to resemble the parabolas with horizontal axis. The equation of each has the form $y^2=a+bx$, y being the speed in revolutions per minute, x the wind velocity in miles per hour, and a and b being constants for any curve. We see that for $x=12$, $y=38$, and that for $x=20$, $y=56$. Hence we have

$$38^2=a+12b, \text{ and}$$
$$56^2=a+20b.$$

Solving these equations, we have $a=-1{,}094$, $b=211.5$, and the equation of the no-load speed curve is

$$y=-1{,}094+211.5x. \tag{8}$$

Proceeding in a similar way, we have for the equation of the 3-pound load speed curve

$$y^2=-1{,}790+214.5x. \tag{9}$$

For the 5-pound load we have

$$y^2=-2{,}304+212x. \tag{10}$$

For the 8-pound load we have

$$y^2=-2{,}715+197x. \tag{11}$$

The speed and starting velocities as computed from these equations and as found by measurement are as follows:

Speed and starting velocities for 16-foot Aermotor No. 44.

Wind velocity per hour.	No load.		3-pound load.		5-pound load.		8-pound load.	
	Measured.	Computed.	Measured.	Computed.	Measured.	Computed.	Measured.	Computed.
8 miles	23.0	24.0	......	......	......	......	......	......
12 miles	38.0	38.0	28.0	28.0	13	15.0	......	......
16 miles	48.0	48.0	41.0	40.0	33	33.0	16.0	20.0
20 miles	56.0	56.0	50.0	50.0	44	44.0	36.0	35.0
25 miles	64.5	65.0	59.0	60.0	54	54.0	47.0	47.0
Starting velocity	4.5	5.1	8.0	8.3	11	10.9	14.5	13.8

The computed values are seen to agree closely with the measured values, so that these speed curves are parabolas of the form $y=\sqrt{a+bx}$. The power curves shown in fig. 43 are parabolas of this form for the reason given for the corresponding case of the 12-foot Aermotor. The curve of maximum power to which these power curves are tangent is a parabola with its axis vertical. Its equation has the form $x^2=a+by$. We may obtain the data for finding the value of a and b by observing that when $x=10$, $y=0.30$; and that when $x=20$, $y=1.55$.
We have

$$10^2=a+0.30b, \text{ and}$$
$$20^2=a+1.55b.$$

Solving these, we have $a=28$, $b=240$, and the equation of the curve is

$$x^2=28+240y. \tag{12}$$

The values of y for four values of x are $x=8$, $y=15$; $x=12$, $y=0.48$; $x=16$, $y=0.95$; and $x=20$, $y=1.55$. It will be seen that these values agree closely with the measured horsepower for these velocities. By making $x=0$ in equation 12 we have $y=-0.125$. The vertex of this maximum power curve is at a distance 0.125 below the axis of x. If the origin of coordinates be changed to this point, equation 12 will take the form $x^2=K\,y'$, K being a constant and y' the horsepower referred to the new origin. Hence we see that the maximum horsepower varies as the square of the wind velocity.

To find the variation of the speed and load for this curve DK, we notice that the 3-pound curve is tangent at $x=10.5$, the 5-pound curve at $x=14$, the 8-pound curve at $x=19$, and the 11-pound curve at $x=24$. The horsepower is known at these points, so that the speed can be found from equation 7.

The wind velocity, load, horsepower, and speed for each of these points are as follows:

Data regarding points of tangency of power curves with curves of maximum power of Aermotor No. 27.

Wind velocity per hour.	Load.	Horsepower.	Revolutions per minute.
	Pounds.		
5 miles	0	0	0
10.5 miles	3	0.33	21
14 miles	5	0.70	26
19 miles	8	1.40	33
24 miles	11	2.17	37

The speeds here found are platted in fig. 42, giving the curve PQ, which gives the speed of the wheel for the maximum load. This curve is seen to be a nearly straight line for velocities above 9 or 10 miles an hour. Hence we may say that the speed increases as the first power of the wind velocity for maximum power.

The load for any wind velocity can now be found from the formula $\text{H. P.} = \frac{176\ \text{L}u}{33{,}000}$, the speed being taken from the speed curve PQ. Or the loads can be measured from the load curve RS, fig. 42. This load curve (RS) for maximum power is seen to be a straight line, showing that for wind velocities above 9 or 10 miles an hour the load for maximum power varies nearly as the first power of the wind velocity.

The following table contains some interesting facts in regard to the working of this mill:

Data in regard to speed of mill No. 44—16-foot Aermotor.

Wind velocity per hour.	No load.			Maximum load.			Ratio of speed at maximum load to speed at no load.
	Revolutions per minute.	Circumference velocity in miles.	Ratio of circumference velocity to wind velocity.	Revolutions per minute.	Circumference velocity in miles.	Ratio of circumference velocity to wind velocity.	
8 miles	23	13.2	1.67	15	8.6	1.08	0.65
12 miles	38	21.7	1.81	23	13.2	1.10	0.61
16 miles	48	27.4	1.71	29	16.6	1.04	0.60
20 miles	56	32.0	1.60	34	19.4	0.97	0.60
25 miles	64	36.6	1.46	38	21.6	0.86	0.60

It will be seen that the ratio of the circumference velocity of the wheel to the wind velocity increases to 12 miles an hour and then decreases. In a 12-mile wind the circumference of the wheel is moving 1.81 times faster than the wind that drives it. It will be seen also that the circumference velocity of the wheel when carrying the maximum load is about equal to that of the wind that drives it, and that the speed of the wheel when carrying a maximum load is about 39 per cent less than its speed when carrying no useful load.

ACTION OF AIR ON THE SAIL OF AN AERMOTOR.

It is not our purpose to discuss this action from a theoretical point of view, but to explain it from the observed and computed results of the 16-foot Aermotor. Fig. 58 shows the concave surface of one sail of a 16-foot Aermotor in a nearly horizontal position as it moves downward; w represents the velocity of the wind, and v the circumference velocity of the sail. The curve JAE, fig. 59, shows the outer end of the sail, and to, in fig. 60, shows the inner end. The cords of these arcs, or the plane of the sail, makes an angle (JOP) of 30° with the plane of the wheel. The point E, fig. 59, represents a particle of air as it comes in contact with the sail when the wheel is carrying its best load; EF represents the velocity of the wind, EH the velocity of this point of the sail; then EG, the other side of the parallelogram constructed on EH and EF, is the velocity of this particle of air over the sail; EG is not tangent to the sail. The point A represents a particle of air as it comes in contact with the moving sail, when the mill is carrying no load; AC represents the relative velocity of the particle of air. It will be seen that the air does not enter the sail tangent to it, but more nearly tangent for best load than for no load.

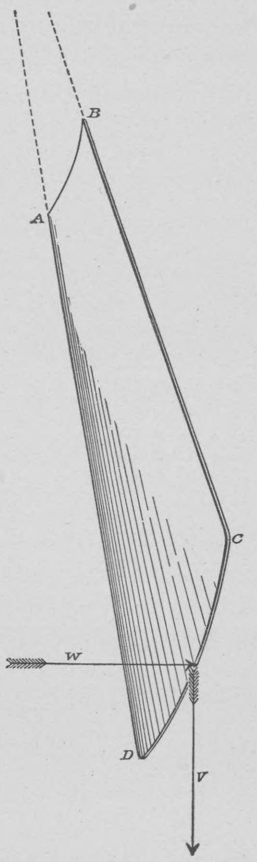


FIG. 58.—Sail of 16-foot Aermotor

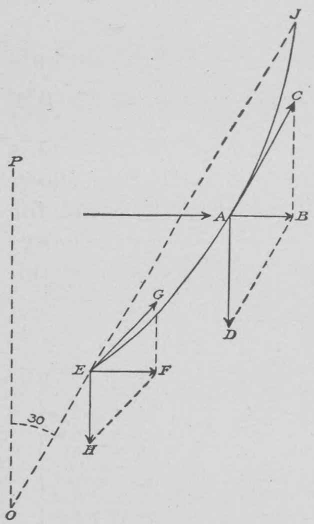


FIG. 59.—Outer end of sail of 16-foot Aermotor.

In fig. 60 t represents a particle of air as it strikes the inner end of the sail when the mill is carrying no load, and a represents a particle of air as it strikes the inner end of the sail when the mill is carrying its maximum load. It will be seen that the air does not strike the sail tangent to it at any place for any load, but that it is most nearly tangent at the outer end of the sail at maximum load. In order for the air to enter the sail tangent to it at maximum load, the angle POJ should be a little greater than 30° at the outer end, and considerably greater than 30° at the inner end. As the load is decreased the angle POJ should be decreased.

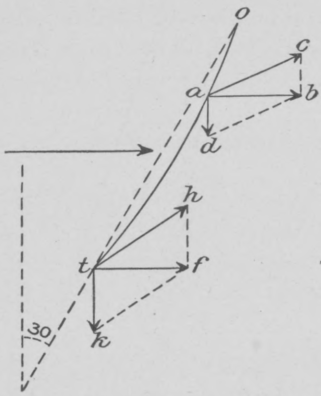


FIG. 60.—Inner end of sail of 16-foot Aermotor.

USEFUL WORK OF TWO POWER MILLS IN A GIVEN TIME.

We can find the useful work of the 12-foot and the 16-foot Aermotors in a year, as we have for two pumping mills (pp. 69–71). For this purpose we will use the mean wind movement at Dodge, Kansas, from 1889 to 1893, as given by Mr. Willis L. Moore, Chief of Weather Bureau.[1] The mean number of hours per month that the wind velocity was 0 to 5, 6 to 10, etc. miles an hour at this place is given in the following table, also the mean horsepower of these two mills for each month. The number of horsepower hours for each mill each month is given at the bottom of the table. The horsepower hours for any month are found by multiplying the number of hours by the horsepower and adding the products.

Table showing useful work of 12-foot and 16-foot Aermotors in a year.

Month.	Mean wind movement at Dodge, Kansas, 1889–1893.							Total hours.	Horsepower hours.	
	0 to 5 miles.	6 to 10 miles.	11 to 15 miles.	16 to 20 miles.	21 to 25 miles.	26 to 30 miles.	31+ miles		12-foot mill.	16-foot mill.
	Hrs.	*Hrs.*	*Hrs.*	*Hrs.*	*Hrs.*	*Hrs.*	*Hrs.*			
January	200.9	253.0	156.2	74.4	37.2	14.9	7.4	744	250.5	358.0
February	176.0	230.1	128.6	74.4	40.6	20.3	6.8	677	251.6	361.5
March	126.5	208.3	178.6	119.0	59.5	29.8	22.3	744	386.6	558.9
April	115.2	172.8	158.4	115.2	72.0	43.2	43.2	720	461.2	671.3
May	119.0	193.5	171.1	119.0	74.4	37.2	29.8	744	433.9	629.4
June	122.4	187.2	136.8	108.0	86.4	50.4	28.8	720	452.0	658.2
July	141.4	215.8	178.6	119.0	59.5	22.3	7.4	744	339.8	489.3
August	178.6	230.6	156.3	96.7	59.5	14.9	7.4	744	297.5	427.6
September	165.6	180.0	151.2	93.6	72.0	36.0	21.6	720	379.6	550.5
October	208.3	230.6	141.4	74.4	52.1	22.3	14.9	744	294.0	423.5
November	194.4	266.4	129.6	64.8	36.0	14.4	14.4	720	244.9	350.9
December	186.0	267.9	141.4	81.8	44.6	14.9	7.4	744	262.2	374.6
Mean	------	------	------	------	------	------	------	------	337.8	487.8
Horsepower 16-foot mill	------	0.13	0.56	1.25	2.00	3.15		------	------	------
Horsepower 12-foot mill	------	0.10	0.41	0.85	1.36	2.12		------	------	------

[1] Some Climatic Features of the Arid Region, by Willis L. Moore. Washington, 1896.

The work done by these mills is greatest at this place in April (461 horsepower hours for the 12-foot and 671 horsepower hours for the 16-foot) and least in November (245 horsepower hours for the 12-foot and 351 horsepower hours for the 16-foot). The mean monthly power is 338 for the 12-foot mill and 488 for the 16-foot mill. Stating these results in another way, we may say that the 12-foot mill at this place will furnish on an average 1.3 horsepower 10 hours a day for 26 days a month, and the 16-foot mill will furnish 1.9 horsepower 10 hours a day for 26 days a month. It must be remembered that the wind velocity on the Great Plains is considerably greater than in the eastern part of the United States, and that consequently the horsepower hours of these mills when used in New York State, for example, will be considerably less than those given in the foregoing table.

MATHEMATICAL DISCUSSION OF TESTS OF JUMBO MILL NO. 55.

On page 46 we have given the results of tests of a 15.5-foot Jumbo mill working two 6-inch pumps. In order more fully to determine the power of this mill and its variation with the number and size of the sails, we have had constructed mill No. 55, shown in Pl. XVI, *B*. It is made of wood, the parts being fastened together with bolts. The diameter is 7.75 feet; length of sails, 11½ feet. There are 8 sails, each made of two boards 11½ feet long and 8 inches wide. There is no governor or other method of regulating the speed of the mill at high wind velocities, as in other mills, but there is a large door or shield on each side. By opening these the mill may be stopped. The mill is not fastened to the ground, but may be moved around by hand so that the wind strikes the sails at right angles. The shaft is 4 by 4 inches and 14 feet long, carefully turned down in a lathe to a diameter of 3 inches near each end. The friction brake is of wood, has an arm about 3½ feet long, and is made so as to fit on the end of the shaft. Oil was freely used on the brake. It was not found practicable to use loads greater than about 6 pounds on a 35-inch arm, as the friction burned the shaft; but the results for the four loads used showed that up to the maximum load the speed of the wheel, or the number of revolutions per minute, varies directly as the load, so that we can easily compute the load and speed for maximum power in any wind velocity. The weight of the wheel with its 8 sails was about 450 pounds. The coefficient of axle friction for well-oiled yellow pine is probably about 0.10, so that the axle friction was about 45 pounds. This weight (45 pounds), acting with a 1½-inch arm, is equivalent to about 2 pounds applied on the brake with a 35-inch arm. The friction on starting is probably 50 to 100 per cent greater than the friction of motion. The 0 brake load then really corresponds to a brake load of 2 or more pounds.

Four sets of tests were made of this mill, numbered 1, 2, 3, and 4. In the first set the full sail area of 8 sails, each 11½ feet by 16 inches, was used. The number of revolutions of the wheel for the four brake loads of 0, 1.75, 2.5, and 4.5 pounds was determined for velocities from 7 to 22 miles an hour. In the second set of tests there were 8 sails, each having an area of 11½ feet by 8 inches; that is, each sail was only half as wide as those used in the first set of tests. In the third set of tests the sail area consisted of 4 sails, each 11½ feet by 16 inches; that is, every other full sail was removed. The fourth set of tests was made to determine the effect of concentrating the air on the sails and reducing the resistance due to air striking the shield and glancing upward by the use of an inclined surface of approach to wheel. This inclined surface had a length of 7 feet and formed an angle of 11° with the horizontal.

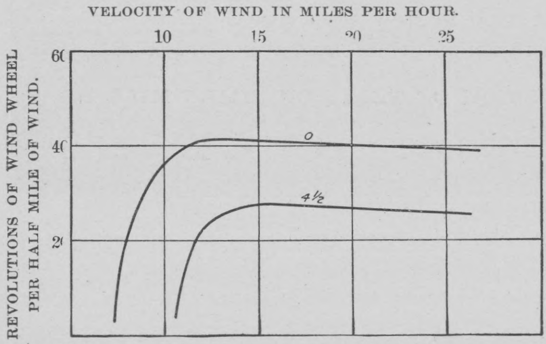


FIG. 61.—Diagram showing revolutions of wind wheel of mill No. 55—7.75-foot Jumbo. Curve marked 0 is for no brake load; curve marked 4½ is for a brake load of 4.5 pounds.

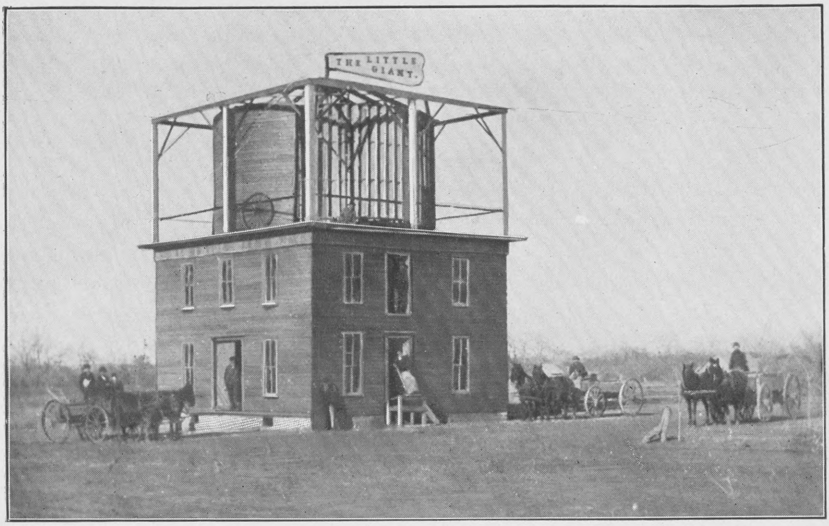
Test No. 1.—In Pl. XVI, *B*, the mill is shown with 8 sails, each 11½ feet by 16 inches. Fig. 61 shows the number of revolutions of the wheel per half mile of wind for two loads—0 and 4.5 pounds—on a 35-inch arm, for the wind velocities shown. These curves for a mill without any means of governing in high velocities are given for comparison with curves of mills having a governor. It will be seen that these curves are nearly horizontal straight lines beyond the point of maximum revolutions per half mile. Thus, for no brake load the revolutions at 12 miles are about 62, and at 25 miles about 59. In a mill with a governor, as, for instance, that shown in fig. 36, the curve is more inclined, or the drop in the number of revolutions is greater.

Fig. 62 shows the number of revolutions per minute for several loads, fig. 63 shows the horsepower.

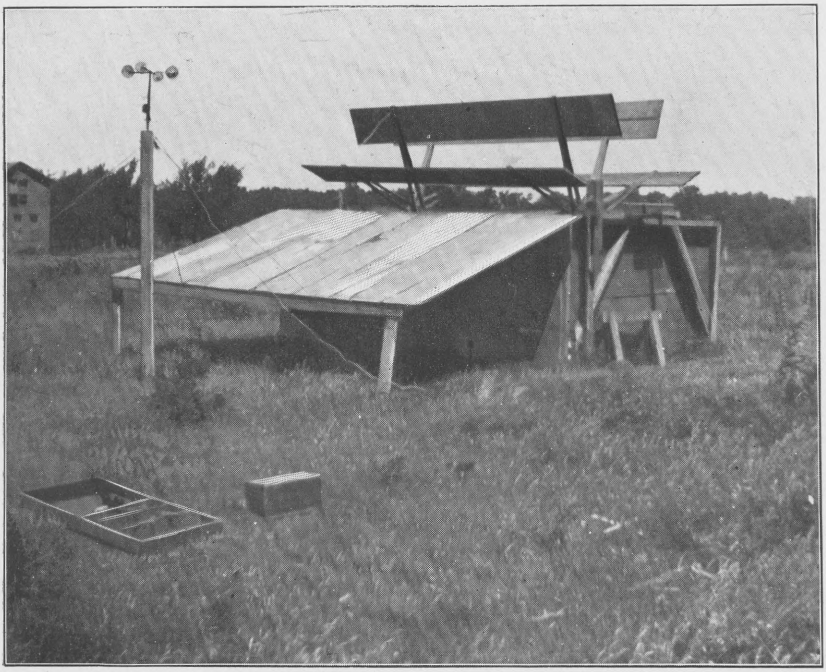
The results of these tests are as follows:

Results of tests of Jumbo mill No. 55 with 8 sails 11½ feet by 16 inches.

Load on brake.	Load per revolution of wind wheel.	Revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Lbs.	*Ft.-lbs.*										
0	0	11	24	33	41	49	------	------	------	------	------
1.75	32.0	------	22	30	38	45	------	0.022	0.030	0.036	0.043
2.5	45.8	------	20	28	36	43	------	0.028	0.039	0.050	0.060
4.5	82.5	------	17	25	33	40	------	0.043	0.063	0.082	0.100



A. VIEW OF MILL NO. 57—24-FOOT LITTLE GIANT.



B. VIEW OF MILL NO. 55—7¾-FOOT JUMBO.

From these results it is seen that the reduction in the number of revolutions per minute is proportional to the load. For example, in a 20-mile wind a $4\frac{1}{2}$-pound load reduces the number of revolutions from 41 to 34, or 1.75 revolutions per brake pound. The power $= 2\pi\ RnL \div 33{,}000$, where $n =$ the number of revolutions of the wheel per minute, $L =$ the load on brake, in pounds, $R =$ the arm of brake (35 inches), $\pi = 3.1416$, and $33{,}000 =$ the number of foot-pounds per minute in a horsepower. We may write the power thus: $P = KnL$, and compute its value as follows, K being a constant equal to $2\pi R \div 33{,}000$:

$$
\begin{array}{llll}
P_0 = K \times 41 & \text{(revolutions)} \times & 0 & (L) = 0 \\
P_1 = K \times 33 & \text{(revolutions)} \times & 4.5 & (L) = 148.5K. \\
P_2 = K \times 26 & \text{(revolutions)} \times & 8.5 & (L) = 221.0K. \\
P_3 = K \times 22.5 & \text{(revolutions)} \times & 10.5 & (L) = 236.3K. \\
P_4 = K \times 20.75 & \text{(revolutions)} \times & 11.4 & (L) = 238.6K. \\
P_5 = K \times 19 & \text{(revolutions)} \times & 12.5 & (L) = 237.5K.
\end{array}
$$

P_4 is seen to be larger than any of the other values of P, and gives an approximate value of the power of the mill for that wind velocity (20 miles).

We may find a more accurate value in an easier way. Let x be the load for maximum horsepower in any given wind velocity. We have seen that 1 pound of load reduces the speed by 1.75 revolutions. Then we can write $P = K\ (41 - 1.75x)\ (x)$. For a maximum value of P we must differentiate P with respect to x, place the first differential coefficient 0, and solve for x. This value of x, according to calculus, makes the power a maximum. Differentiating, we have $P \div dx = 41 - 2\ (1.75x) = 0$. Solving for x we have $x = 11.7$ pounds. The corresponding value of the revolutions of the wheel per minute is $41 - 1.75 \times 11.7 = 20.5$ revolutions.

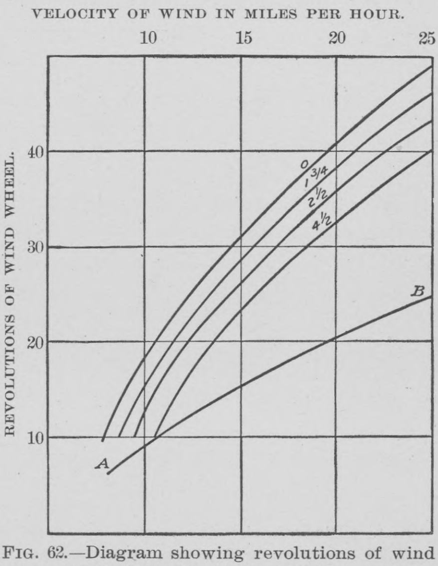


FIG. 62.—Diagram showing revolutions of wind wheel of mill No. 55—7.75-foot Jumbo. Curves marked 0, $1\frac{3}{4}$, $2\frac{1}{2}$, and $4\frac{1}{2}$ are for brake loads of 0, 1.75, 2.5, and 4.5 pounds, respectively; AB is for best load.

For a 25-mile wind we have $x = 49 \div 3.5 = 14$ pounds, and $n = 16.5$. In a similar way we get the load and revolutions for maximum power for other wind velocities. These and the corresponding horsepowers are as follows:

Values for the curve DK (maximum power) fig. 63.

Wind velocity (miles per hour).	Load in pounds.	Revolutions of wind wheel per minute.	Horsepower.
8	3.1	6.0	0.010
12	7.0	12.0	0.046
16	9.4	16.5	0.086
20	11.7	20.5	0.133
25	14.0	24.5	0.190

The curve *DK* is nearly a parabola. The revolutions per minute for the best load are seen to be very nearly equal to the wind velocity

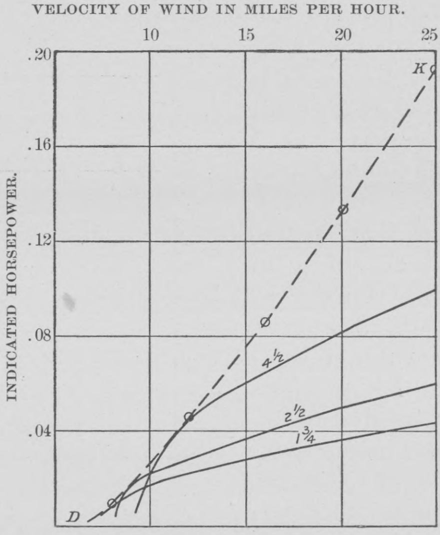


FIG. 63.—Diagram showing horsepower of mill No. 55—7.75-foot Jumbo. The curves show the horsepower for brake loads of 1.75, 2.5, and 4.5 pounds, respectively; dotted curve *DK* shows maximum power.

in miles. These are platted in fig. 62, giving the line *AB*, which is nearly straight.

RELATION BETWEEN WIND VELOCITY AND CIRCUMFERENCE VELOCITY OF WHEEL.

If we multiply the number of revolutions of the wind wheel for any wind velocity by 24.4 feet (the circumference of the wheel) and divide by the wind velocity, in feet per second, we have the following results for no brake load and for best load:

Table showing ratio between wind velocity and circumference velocity of wheel.

Load.	Wind velocity per hour.				
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
No load	0.38	0.55	0.57	0.57	0.55
Best load	0.21	0.27	0.28	0.28	0.27

From this we see that the velocity of the circumference of the wheel is not more than 57 per cent of the velocity of the wind. For velocities above a certain amount it remains nearly constant for any load. It will be seen too that the speed of the wheel for best load is almost exactly half that for no brake load.

Test No. 2.—Sail area, 11½ feet by 8 inches—each inner half sail removed. The results of this set of tests are as follows:

Results of tests of Jumbo mill No. 55, with 8 sails 11½ feet by 8 inches.

Load.		Revolutions of wind wheel per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	9	22	30	39	47	....	....	....	....	....
3.25	59.6	......	17	26	32	40	....	0.031	0.047	0.058	0.072

By comparing these results with those of test No. 1 it will be seen that the number of revolutions per minute for no load is from two to three times less when the half sails are used. The 3½-pound load with half sails gives about the same speed as the 4½-pound load with whole sails. The weight of the wheel is reduced about 40 per cent, which makes the reduction in speed less than it would be if the weight of the wheel remained constant. It will be seen, then, that for this size of wheel very little power is gained by the use of the inner 8-inch board of each sail. It is quite likely that sails 12 inches wide would give fully as much power as sails 16 inches wide.

Test No. 3.—The sail area was 4 sails, each 11½ feet by 16 inches—every other full sail removed. The results of this set of tests were almost the same as those of test No. 1. There was no measurable reduction in the speed of the wheel when every other full sail was removed. The weight of the wheel was reduced about 40 per cent, and consequently the friction. The gain in pressure on the extra sail area is counterbalanced by the additional friction.

Test No. 4.—The sail area was 8 sails, each 11½ feet by 16 inches—the same as for test No. 1. There was an inclined surface (shown in Pl. XVI, *B*) for concentrating air on sails and in a measure preventing an upward current from the front shield. The results of this set of tests are the same as those of No. 1. There was no measurable increase in the number of revolutions when the mill was loaded or unloaded, or when the incline was used or not used.

For this size of mill 4 sails each 12 inches wide give the maximum power. From our tests of other mills we should say that the sail width should increase directly as the diameter increases. For diameters of 12 feet or more it is likely that the addition of one or two more sails, say 5 for a 12-foot mill and 6 for a 16-foot mill, may increase the power over that for 4 sails.

In 1895 we made some measurements of the pressure of air on small curved surfaces,[1] from which we infer that if galvanized-iron sails curved to a radius about twice the width and with the concave surface to the wind were used the power of the mill would be increased about 15 per cent over that with the plane fans.

Putting the results of these tests of Jumbo mills in the most practical form, we have the following as the proper sail area and the probable horsepower of wooden Jumbo mills in a 16-mile wind when properly loaded, assuming the power to increase as the square of the diameter:

Table showing proper sail area and probable horsepower of Jumbo wooden mills in a 16-mile wind.

Diameter of wheel.	Number of sails.	Width of sails.	Length of sails.	Horsepower.
		Inches.	*Feet.*	
8 feet	4	12	12	0.09
12 feet	5	18	12	0.20
16 feet	6	24	12	0.36
20 feet	6	30	12	0.56

The formula used for computing the pressure on a series of plane surfaces moving in the direction of the velocity of the wind is—

$$P=F\frac{r}{g}(c-v)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

In this F is the area, in square feet, of the vane, r the heaviness of air at the observed temperature and barometric pressure, c the velocity of wind, and v the velocity of wind wheel, each in feet per second.

The heaviness of the air is found from the formula—

$$r=ro\frac{B}{Bo}\frac{To}{T} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

In this To is the absolute temperature in centigrade degrees.

[1] Kansas University Quarterly, Vol. IV, July, 1895.

From equation b we have $r=0.08\times\frac{29}{30}\times\frac{273}{301}=0.07$ pound per square foot. From the table on page 123 it will be seen that for maximum power in a 16-mile wind $v=0.28c$. Substituting in equation a we have, for the pressure on one sail—

$$P=11.5\times\frac{1}{32.2}\times0.07\,(1-0.27)^2\,c^2=4.1 \text{ pounds.}$$

The arm of this pressure about the axis of the wheel is about 3.06 feet. Hence the moment of this force is $4.1\times3.6=14.76$ foot-pounds. This moment is equal to the moment of the brake load, and we have $14.76=35x$, and $x=4.24$ pounds. The load actually carried on the brake, including friction, is about 8 pounds; hence nearly half of the working pressure comes from wind pressure on the approaching and receding sails, or only a little more than half the pressure comes from the sail which is at the highest position possible.

MATHEMATICAL DISCUSSION OF TESTS OF LITTLE GIANT MILL NO. 56.

This is a 4.67-foot mill made by Mr. C. Hunt, of Wichita, Kansas. These mills are made in sizes from 4 to 24 feet in diameter, to rest on a low tower or on a building. The largest one yet built is shown in Pl. XVI, *A*. It is used for grinding wheat. The Little Giant mill will be seen to resemble the Jumbo in that the wind wheel moves in the direction of the wind and not across it. It differs from the Jumbo, however, in having a vertical axis and many curved iron sails, instead of a horizontal axis and few plane wooden sails. The wind is prevented from striking the sails as they come around toward the wind by a shield which, when closed, covers about one-third of the circumference. The shield can move freely about the axis of the mill and has hinged to it a wing which can be held at right angles to the circumference. There is also a vane fastened to the shield, to aid in the government of the mill. When the wing of the shield is closed, the vane takes the direction of the wind and places the shield directly in front of the wind wheel, shutting off the wind from the wheel. When the wing is open, the pressure of the wind against it carries the shield around, admitting the wind to one-half of the wheel. By properly placing the vane and using the proper weight on the wing, the wind is admitted to a small or a large portion of the wheel, and thus the speed of the wheel is regulated. The mill receives the wind from all directions and regulates automatically.

Mill No. 56 has 24 curved iron sails, each 3 feet $10\frac{1}{2}$ inches long and $6\frac{1}{2}$ inches wide, set at an angle of 27° to the radius. The radius of curvature of the sails is $7\frac{1}{2}$ inches. The vertical shaft of the wind wheel has a beveled cogwheel, which gears into another beveled cogwheel on a short horizontal shaft. The latter has a pitman for working a pump. The horizontal shaft on which the brake was placed was geared back 43÷13. The brake arm was 2 feet $10\frac{1}{2}$ inches long. The number of revolutions per minute of the brake shaft was found for the four loads 0, 2, 4, and 6 pounds, respectively. The corresponding speed of the wind wheel is found by multiplying by $3\frac{1}{4}$. The results of the tests were as follows:

Results of tests of Little Giant mill No. 56.

Load.		Revolutions of brake shaft per minute at given wind velocities (per hour).					Horsepower at given wind velocities (per hour).				
		8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
Pounds.	*Ft.-lbs.*										
0	0	10	19	25	31	38	--------	--------	--------	--------	--------
2	35.7	6	16	21	27	34	0.007	0.017	0.023	0.030	0.040
4	71.4	------	11	18	23	30	--------	0.024	0.039	0.050	0.065
6	107.1	------	6	14	19	26	--------	0.019	0.045	0.062	0.084

Referring to fig. 64, the mill will be seen to start for no load in a light wind—about 5 miles an hour. More than half of each speed curve is a nearly straight line. This is due to failure to govern, the mill being held wide open all of the time. It will be seen that each pound of load reduces the speed about two revolutions per minute for about 0.67 of each curve. Fig. 65 shows the brake horsepower for three loads—2, 4, and 6 pounds, respectively. The curve DK, to which these load curves are tangent, shows the maximum power of the mill. This curve passes through the points y (horsepower)=0 when x (wind velocity)=5, and y=0.024 when x=12. Hence, if we assume this curve DK to be a parabola, we have for its equation—

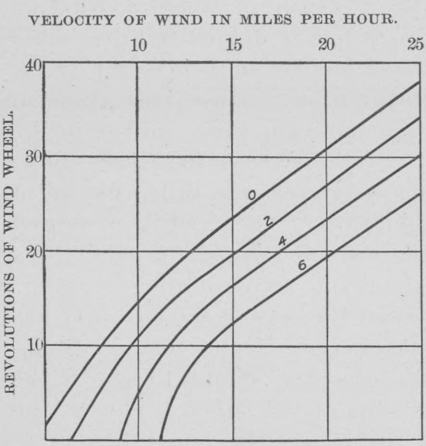


FIG. 64.—Diagram showing revolutions of wind wheel of mill No. 56—4.67-foot Little Giant. The curves marked 0, 2, 4, and 6 are for brake loads of 0, 2, 4, and 6 pounds, respectively.

$$x^2 = 496y + 25.$$

The horsepower from this equation and from fig. 65 is as follows, y' being taken from fig. 65:

Horsepower of mill No. 56 at given wind velocities.

x	y	y'
5	0.000	0.000
8	0.008	0.007
12	0.024	0.024
16	0.046	0.045
20	0.075	0.065

It will be seen that the horsepower of this mill does not increase as fast as the square of the wind velocity. From fig. 65 it will be seen that the 2-pound curve is tangent at 8 miles, the 4-pound curve at 12 miles, and the 6-pound curve at 16 miles an hour. Hence the load for maximum power increases about as the first power of the wind velocity. The speed of the brake shaft for these loads is 6, 11, and 14 revolutions per minute, respectively. Hence the speed of the wind wheel does not increase as fast as the first power of the wind velocity. The ratios of circumference velocity of wind wheel to wind velocity for no load and for maximum load for five wind velocities are as follows:

Table showing relation of circumference velocity of wind wheel to wind velocity.

Wind velocity per hour.	No load.			Maximum load.			Ratio of revolutions at maximum load to revolutions at no load.
	Revolutions of brake shaft per minute.	Circumference velocity in miles per hour.	Ratio of circumference velocity to wind velocity.	Revolutions of brake shaft per minute.	Circumference velocity in miles per hour.	Ratio of circumference velocity to wind velocity.	
8 miles	10	5.2	0.65	6	3.1	0.39	0.60
12 miles	19	9.9	0.74	11	5.7	0.47	0.58
16 miles	25	13.0	0.81	14	7.3	0.46	0.56
20 miles	31	16.1	0.80	16	8.3	0.42	0.52
25 miles	38	19.8	0.79				

From this we see that for no load the greatest circumference velocity is only 81 per cent of the wind velocity. For best load the ratio is 47 per cent. Here is the great disadvantage of these wheels, which move in the direction of the wind instead of across it—they move too slowly. The ratio of circumference velocity to wind velocity in an Aermotor is 1.75. This is 2.16 times the greatest corresponding circumference velocity of the Little Giant mill.

COMPARISON OF LITTLE GIANT AND JUMBO MILLS.

From the following table it will be seen that the circumference velocity of the Jumbo is only from 0.55 to 0.70 of that of the Little Giant for best load. The horsepower of the Jumbo is about 1.9 times that of the Little Giant; the ratio of the Jumbo diameters is 1.67;

hence the ratio of the power is a little greater than that of the diameters. It must be remembered, however, that the Jumbo is about three times the length of the Little Giant. For the same sail lengths the latter does 1.57 more work than the Jumbo.

Comparative data of Little Giant and Jumbo mills.

Mill.	Maximum horsepower at given wind velocities (per hour).					Circumference velocity for maximum load at given wind velocities (per hour).				
	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.	8 miles.	12 miles.	16 miles.	20 miles.	25 miles.
7¾-foot Jumbo	0.010	0.046	0.086	0.133	0.190	1.7	3.40	4.70	5.80	......
4⅜-foot Little Giant	0.007	0.024	0.045	0.066	0.100	3.1	5.70	7.30	8.30	......
Ratio	1.4	1.9	1.9	2.0	1.9	0.55	0.60	0.64	0.70	......

Taking into account the difference in the diameters of the wind wheels of these mills, we may say that the Little Giant will furnish about 2.5 more power than the Jumbo for the same diameter and length of sail. The Jumbo requires a 7-mile wind to start it with no load; the Little Giant will start with no load in less than a 5-mile wind. The Jumbo has no means of governing; the Little Giant governs easily and completely. The Jumbo gets the full pressure of the wind when it comes from two directions only; the Little Giant works equally well with the wind from any direction. The Little Giant is less likely to be injured in a windstorm than the Jumbo. The first cost of the Jumbo is somewhat less than that of the Little Giant. A 5-foot Little Giant with stub tower can be bought for about $15.

COMPARISON OF LITTLE GIANT WITH 8-FOOT AERMOTOR.

The efficiency of the pump and well of Aermotor No. 5 (for description and results of tests, see pages 33 and 34, Part I) is probably about 60 per cent. For the speeds and horsepowers of these mills we have the following:

Comparative data of Little Giant and 8-foot Aermotor.

Mill.	Load per revolution of wind wheel.	Sail area.	Revolutions of wind wheel per minute at given wind velocities (per hour).				Horsepower at given wind velocities (per hour).			
			12 miles.	16 miles.	20 miles.	25 miles.	12 miles.	16 miles.	20 miles.	25 miles.
	Ft.-lbs.	*Sq. ft.*								
8-foot Aermotor (No. 5)	45	34	62	84	99	115	0.084	0.115	0.138	0.158
4⅜-foot Little Giant (No. 56)	24	54	34	55	71	92	0.024	0.039	0.050	0.065
Ratio	1.96	0.63	1.82	1.53	1.40	1.25	3.50	3.00	2.76	2.43

It will be seen that the sail area of the Aermotor is only 0.63 that of the Little Giant, that the wind wheel of the former makes from 1.25 to 1.82 more revolutions per minute than the latter, and that the power of the former is from 3.5 to 2.4 times greater than the power of the latter. While the sail area of the Aermotor is only 0.63 that of the Little Giant, the wind area of the former is much greater than that of the latter. The wind can not enter the wheel of the Little Giant over an area greater than the radius multiplied by the length of the sail, or 9.1 square feet. In the Aermotor the wind enters the wheel over an area equal to the difference between the areas of the two circles, one having a diameter of 8 feet, the other having a diameter of 3 feet. This wind area is 43.2 square feet. Hence the wind area of the Aermotor is $43.2 \div 9.1 = 4.75$ times that of the Little Giant. Here is the great advantage that the Aermotor has over the Little Giant—it has only 0.63 of the sail area, and hence cost less for sails, and 4.75 times more air strikes its sails than strikes those of the Little Giant. It will be shown later that in the Little Giant the air acts on its sails while passing out of the wind wheel as well as while passing into the wheel, and thus the power for the same wind area is greater in that mill than in the Aermotor.

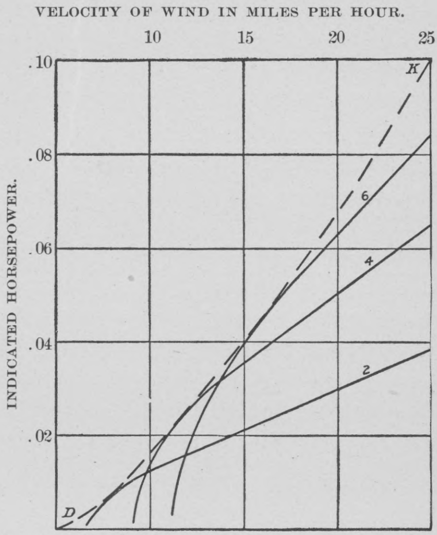


FIG. 65.—Diagram showing horsepower of mill No. 56—4.67-foot Little Giant. The curves marked 2, 4, and 6 show horsepower for brake loads of 2, 4, and 6 pounds, respectively; dotted curve *DK* shows maximum power.

Fig. 66 is a diagram showing the action of the wind on the sails of the Little Giant mill. *AH*, *BK*, etc., are the curved sails. The cord *AH* makes an angle of 27° with the radius *AP*. *CD* is the shield, with the wing *DE* open. Let *Aa* represent the direction and magnitude of the wind with respect to the earth. We have seen that for maximum load the ratio of the circumference velocity of the wheel to the wind velocity is 0.47; hence drawing *Ac* tangent to the circumference *Aa* and equal to 0.47 of *Aa*, and completing the parallelogram on them, we have *Ab* representing the direction of the wind with respect to the moving sail. If we assume this to be the velocity of the air over the sail (it is somewhat less than this, since *Ab* is not quite tangent to the sail at entrance), we can construct the path of a particle of air with respect to the earth. The points 1, 2, and 3 are on this path, and *L3* gives the approximate direction of the particle of air through the wheel. At *L* we combine this velocity with the inner circumference velocity of the sail, giving the velocity Lp with respect to the moving sail. This is seen to make a large angle with the tangent at entrance, reducing its magnitude somewhat. $L4$ is approximately the absolute path of the particle over the sail, and 4-5 is the direction of the particle at exit. $B6$ represents the absolute path of a particle of air as it moves over the sail BK. This particle of air passes through the

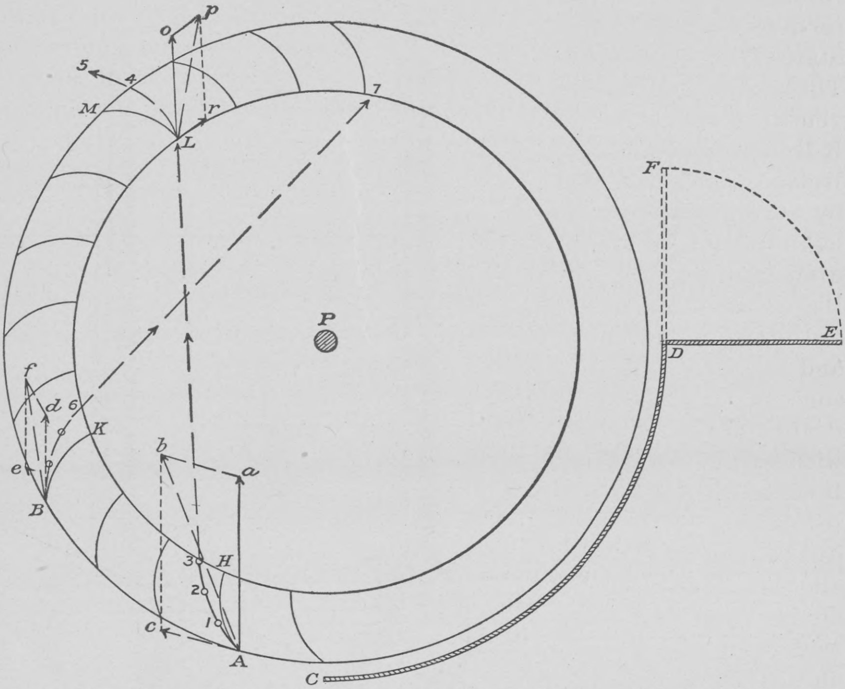


FIG. 66.—Diagram showing action of wind on sails of mill No. 56—4.67-foot Little Giant.

wheel in the direction 6-7. The path 6-7 of this particle crosses the path of the particle from 3; hence there is interference inside the wheel, which prevents our tracing with accuracy the path of a particle out of the wheel. It is evident, however, that after passing into the wheel the air strikes the concave side of the sails on the opposite side, and aids in pushing the wheel around, so all the work is not done by the sails on the side where the air enters.

INDICATED AND TRUE VELOCITIES.

Thus far all of our results for speed and power of windmills are given in terms of indicated velocities, that is, velocities as read from the Robinson cup anemometer. It is necessary, or at least desirable, to examine these to see whether they agree with true velocities or distances actually passed over by the wind per hour. Fig. 67 shows the Robinson cup anemometer as used by the United States Weather Bureau. This instrument was invented in 1846 by Dr. T. R. Robinson, of Armagh, Ireland, and is now used by several meteorological bureaus for the measurement of wind velocity. It gives a continuous record of wind movement and requires no device, such as a vane, to give it the proper direction with respect to the wind. It is made so that each 50 revolutions of the cups can be read on the dial, and there is an electrical device for recording each 250 or each 500 revolutions of the cups.

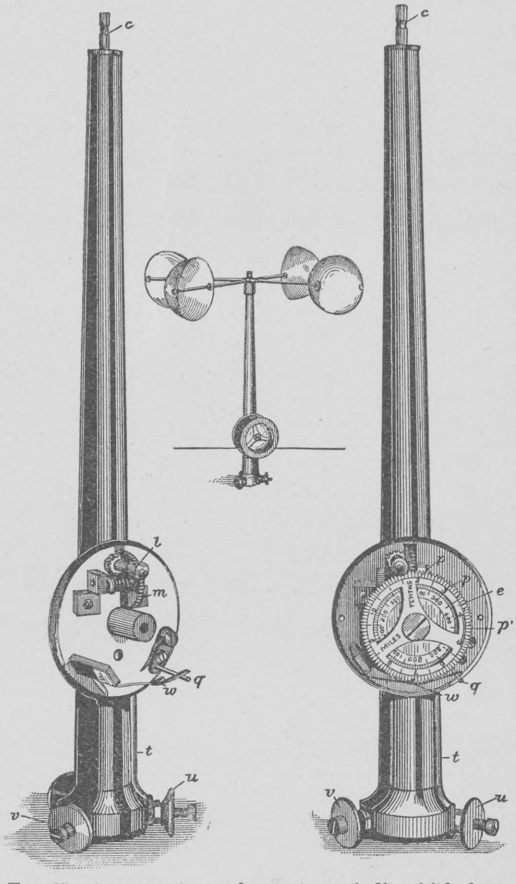


FIG. 67.—Anemometer and cups. c, spindle which forms the axis of revolution of the cups; m, 50-tooth wheel which engages an endless screw on the end of the spindle; l, small toothed wheel which engages an endless screw on the axis of the wheel m; e, pair of dial wheels which are moved by the wheel l; p, one of ten contact pins to aid in closing the electric circuit at the end of each mile of wind; p', two of these pins connected, forming the tenth mill pin; w, contact spring; q, a contact point at the end of contact spring; t, small insulated tube connecting q with the insulated binding post u and with the second binding post v.

Referring to fig. 68, let $A =$ the upper and $B =$ the lower cup of a Robinson anemometer rotating about the axis, let c equal the velocity of the wind, and v the velocity of the cup center, each in feet per second; $x =$ the ratio of the velocity of the wind to that of the cup center, $P_1 =$ the pressure on the concave surface, and $P_2 =$ the pressure on the convex surface of the cup. Dr. Robinson found from sixteen experiments with stationary cups exposed to wind of several velocities that for all velocities the pressure when the concave surface of the cup is toward the wind is about four times that when the convex surface is presented to the wind. The pressure on the moving cup A is $P_1=K_1 Fr (c-v)^2 \div 2g$,[1] and the pressure on the cup B is $P_2=K_2 Fr (c+v)^2 \div 2g$; F being the area of the cup, K_1 and K_2 being constants the ratio of which, as found by Robinson, is 4, r the heaviness of air, and $c+v$ and $c-v$ the relative velocities of the cups. Neglecting friction in the anemometer, inertia of cups and arms, and the influence of two of the cups until they are near the position shown in fig. 68, we see that for uniform velocity P_1 must equal P_2; if P_1 is greater than P_2, v will increase; if P_1 is less than P_2, v will decrease. We have, therefore, for uniform velocity $K_1\ Fr\ (c-v)^2 \div 2g = K_2\ Fr\ (v+c)^2 \div 2g$ or $4\ (c-v)^2 = (c+v)^2$. This equation can be put in the form $4\ (x-1)^2=(x+1)^2$. Solving we have $x=3$; that is, the velocity of the wind is three times that of the cup centers. For an anemometer having arms 6.72 inches long, the distance passed over by a cup center in 500 revolutions is $d=\frac{2\times 22}{7} \times \frac{6.72}{12} \times 3 \times 500=5{,}280$ feet, or 1 mile.

Dr. Robinson believed that this ratio of wind velocity to that of cup center was true for all velocities, and consequently the makers of the instrument have marked the dial in miles. We shall see, however, from the rating of the one that we have used in these windmill tests that this ratio is not a constant. It will be seen that for wind of uniform velocity this ratio is a variable which has the value 3 for 9 miles an hour, is greater than 3 for less velocities, and is less than 3 for greater velocities than 9 miles an hour; in other words, to get true velocities we must add a correction below 9 miles an hour and subtract a correction above that velocity. Friction and inertia were neglected in deriving the foregoing value of this ratio. The former has little influence in an instrument kept in good condition, but in a poorly kept instrument it may have a large influence for low velocities. This ratio has been found to be 8 to 10 with much friction. The inertia of the arms and cups has a marked influence on this ratio, especially for ordinary gusty wind. As the

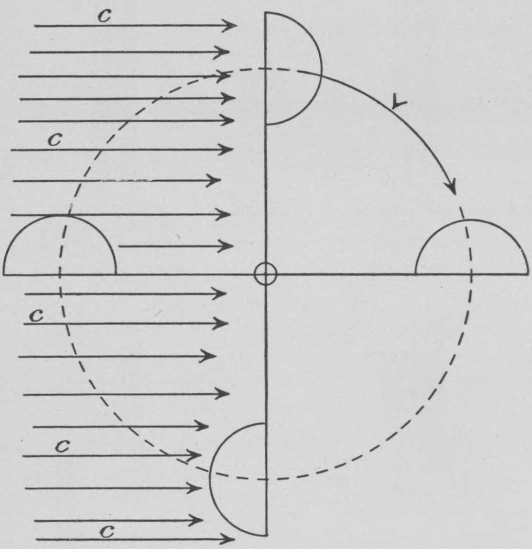


FIG. 68.—Diagrammatic section of anemometer cups.

[1] Church's Mechanics of Engineering, p. 815.

gustiness of the wind increases the correction to be subtracted to get the true velocity increases also.

The relation between the indicated and true velocity of an anemometer is found by moving the anemometer in still air at different velocities, and noting the distance passed over, also the readings of the instrument. It is seldom that the air out of doors is still for any considerable length of time, so that this comparison is usually made within an inclosure, the anemometer being carried around in a circle. The radius of the whirler should be as long as possible, and made so as to affect the circulation of air as little as possible, and to reduce the effect of the centrifugal force.

The whirling machine that we have used for rating the anemometer is the property of the United States Weather Bureau. It consists essentially of an arm 28 feet long and 8 feet above the ground, on the end of which the anemometer is carried at an elevation of 2 feet above the arm. This arm is counterweighted and is stiffened by the rods. It is clamped to a vertical shaft, which carries a cogwheel near its lower end. A cogwheel on a horizontal shaft engages the large cogwheel and gives rotation to the arm. For low velocities the power was applied through a crank on the horizontal shaft, and for higher velocities by a crank on a second shaft, the latter working the first shaft by means of two sprocket wheels and a chain. The machine was set up out of doors, in a sheltered place away from any building, and was used on several nights when there was scarcely any wind. It was made to rotate about half the time in the positive direction and the other half in the negative direction.

A new Robinson anemometer was used with which to compare results obtained for the one used in our windmill tests. The results for these instruments agree quite closely. The results obtained on December 29, when there was no perceptible wind, are as follows:

Table showing relation between indicated and true velocity of anemometer.

Indicated velocity, in miles per hour.	Revolutions of long arm in ½ mile of wind.	True velocity, in miles per hour.	Correction, in miles.	Correction, in miles, for gusty wind.
6	15.5	6.20	+0.20	0
8	15.1	8.05	+0.05	−0.2
11	14.7	10.78	−0.22	−0.6
15	14.2	14.20	−0.80	−1.2
20	13.8	18.40	−1.60	−2.2
25	13.53	22.55	−2.45	−3.2
30	13.3	26.60	−3.40	−4.3

It will be seen that the indicated velocity is less than the true velocity for velocities less than 9 miles an hour; above 9 miles the true velocity is less than the indicated velocity. In other words, the correction is added below 9 miles an hour and subtracted above that velocity. It will be seen that up to 11 miles an hour these anemometer readings differ very little from the true readings, but for higher velocities the correction becomes quite large. The last column of the foregoing table gives the corrections to be applied to the indicated velocities of the Weather Bureau Robinson anemometer for gusty wind.[1] The motion of ordinary moving air, when studied with a very light anemometer recording each revolution, is found to vary suddenly by large amounts. The rate of motion changes 20 or 30 miles an hour in a few seconds.[2] The record of the standard Robinson anemometer, recording miles or half miles, does not show these sudden changes, but gives an average velocity for the wind. Its

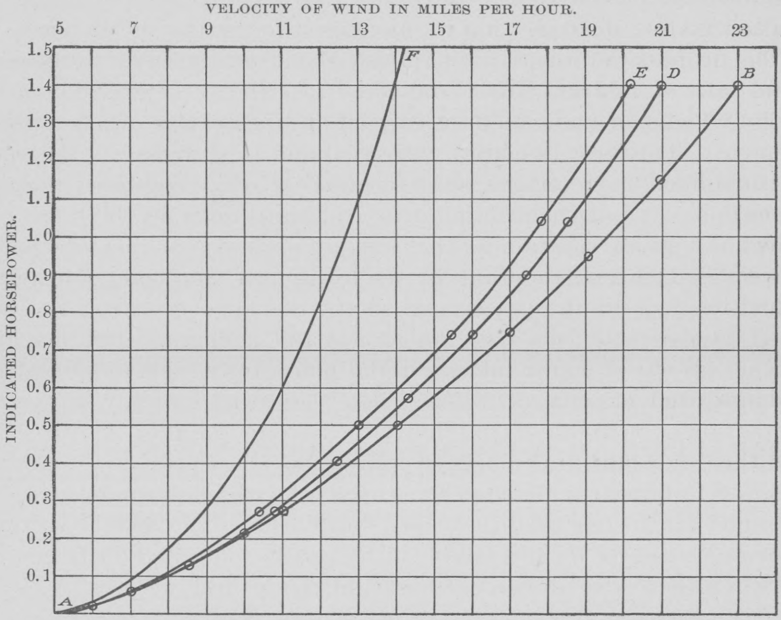


FIG. 69.—Diagram showing horsepower of mill No. 27—12-foot Aermotor. Curve *AB* shows power for indicated velocity, assuming wind to be not gusty; *AD* shows power for true velocity; *AE* shows power in average gusty wind; *AF* shows power from H. P. $=\frac{x^3-140.6}{2{,}086}$.

weight and consequent inertia cause it to continue its rotation for a time after the impulse is passed, and when the next impulse strikes the cups their weight will not allow them to take the velocity of the impulse. The less the weight the more nearly will the velocity of the cups be that of each gust. The effect is that the cups revolve faster in a gusty wind of, say, 20 miles an hour, than in wind of the same velocity but not gusty. Two difficulties arise in dealing with gusty wind: (1) The gustiness of any wind varies from time to time, and the anemometer gives no indication of it; (2) we have no means of producing artificial gusty wind in which to rate anemometers. If the anemometer is rated in natural wind, then a correction

[1] Anemometry, by C. F. Marvin. Washington, 1893.

[2] The Internal Work of the Wind, by S. P. Langley. Washington, 1893.

must be applied, but its amount is uncertain. The velocity of gusty wind can not, therefore, be measured with certainty. This, however, does not lessen the value of the Robinson anemometer as an instrument for measuring wind velocity, nor introduce an error in our results. For a given velocity and gustiness the anemometer will always give the same reading, and the same gusty wind which strikes the anemometer strikes the windmill directly behind it. The difficulty arises when we try to compare results in which the Robinson anemometer was used in measuring velocity with those in which some other form of anemometer was used. The corrections given in the last column of the table were found by Prof. C. F. Marvin, of the United States Weather Bureau, and are for ordinary gusty wind.

The Robinson anemometer is now so generally used to measure wind velocity that it is better to express the speeds and powers of windmills in terms of these than of any other. If results are desired in terms of true velocities, they can be found approximately by means of the table of corrections given on page 133. Fig. 69 shows the power of mill No. 27 expressed in terms of three kinds of velocity: *AB* shows the power assuming the wind to be not gusty; *AD* shows the power for true velocity, that is, after applying the corrections in the fourth column of the table; *AE* shows the power in average gusty wind, that is, after applying the corrections in the last column of the table; *AF* would give its power if the power increased as the cube of the indicated velocity.

COMPARISON OF WRITER'S EXPERIMENTS WITH THOSE OF OTHERS.

Comparison with Smeaton's experiments.—In this comparison we use indicated velocities and results for best mills. Smeaton's results are given on pages 15 and 16, Part I. It will be remembered that his wheels were 3.5 feet in diameter, moved against still air in a circle of 5.5 feet radius, and that his wind velocities varied from 3 to 6 miles an hour.

Smeaton found (maxim 1, page 15, Part I) that the velocity of a windmill sail, whether loaded, so as to produce maximum power, or unloaded, is nearly as the velocity of the wind. We have found that the velocity of wind wheel when loaded increases nearly as the wind velocity, but when it is unloaded it increases as the square root of the wind velocity.

Smeaton found (maxim 3) that the maximum power increases somewhat less rapidly than as the cube of the wind velocity. We have found that the maximum power increases as the square of the wind velocity—for true velocities somewhat faster than as the square of the wind velocity.

Smeaton found (last part of maxim 5) that the power for a constant load increases as the first power of the wind velocity. Our experiments show that for a constant load the power increases as the square root of the wind velocity.

Smeaton found (maxim 6) that the circumference velocities of similarly made mills of different diameters vary inversely as the diameters. We have found this to be true.

Smeaton found (maxim 8) that the maximum power for similarly made mills increases as the squares of the diameters. We have found that it increases about as the 1.25 power of the diameters.

Smeaton found (maxim 9) that the circumference velocity of the Dutch sail, whether loaded or unloaded, is considerably greater than the wind velocity. We find that it is nearly equal to the wind velocity for loaded sail, and about 1.75 times the wind velocity for the unloaded sail.

Comparison with Coulomb's experiments.—In this comparison indicated velocities are used. Coulomb's observations (see page 16, Part I) were made on a Dutch mill (fig. 1, Part I) having a wind wheel 70 feet in diameter. He found that at a wind velocity of about 15 miles an hour the wind wheel was making 13 revolutions per minute and yielding about 7 horsepower of useful work. Comparing this with the results for the 16-foot Aermotor for maximum load, we have the following:

Comparison of results of tests of Coulomb's 70-foot mill with writer's 16-foot Aermotor.

Mill.	Revolutions of wind wheel per minute.	Circumference velocity in feet per minute.	Horsepower.
70-foot mill	13	2,860	7.0
16-foot Aermotor	28	1,408	0.8

The circumference velocity of the large mill is more than twice that of the smaller one. The ratio of the powers is $7 \div 0.8 = 8.8$. The ratio of the diameters is $70 \div 16 = 4.4$. The ratio of the powers is about twice that of the diameters. The ratio of the squares of the diameters is 19.14.

It is very likely that the wind velocity as found by Coulomb is too small; the very large circumference velocity of his wheel indicates this. It is probable that the wind velocity during his observations was about 20 miles an hour instead of 15. In a 20-mile wind the horsepower of the 16-foot mill is about twice that in a 15-mile wind, and the speed 34 revolutions per minute against 28. The ratio of the horsepowers would then be about as the diameters of the wind wheels.

Comparison with Griffiths's experiment.—The performance of a pumping windmill depends on so many factors, most of which may affect the result to a large degree, that it is doubtful whether it is worth while to make a comparison where the conditions differ much. There is the pump efficiency alone, other conditions being the same, which may make the horsepower of one four or more times that of the other. For example: Both mills have a brake power of 1 horsepower; one mill works a pump which has an efficiency, under present conditions, of 20 per cent, its useful horsepower being 0.2; the other mill operates a pump which has an efficiency of 80 per cent, its horsepower being 0.8, or four times that of the other. We have seen that for wind velocities above a certain amount the power increases nearly as the load, so that by doubling the load for the higher velocities the power is doubled. The gearing and means of governing affect the power in a somewhat less degree. The way in which the wind velocity is measured may affect the recorded power and speed. If the wind wheel, or tower, or any other obstacle obstructs the free flow of the air to the anemometer, the recorded velocity will not be as great as it should be. If the anemometer is placed on the platform, it will give a less velocity than if held some distance in front of the wheel and at the height of the axis. The temperature and barometric pressure affect the power.

In Mr. Griffiths's data (see pages 17 and 18, Part I) the load factor is known, but the wind velocities he gives are small, and for small velocities it is difficult to compute the effect on the power of differences in load. In fact, most of his velocities are less than are required to start irrigating mills. Only four of his mills, viz, Nos. 1, 2, 5, and 6, are comparable with mills that we have tested. The mills with which we have compared them are Nos. 36, 38, and 47—very lightly loaded mills with low pump efficiency.

Comparison of results of Griffiths's tests with those of writer's tests.

Mill.	Outer diameter of sail.	Load per stroke of pump.	Wind velocity.	Strokes of pump per minute.	Horsepower.
	Feet.	*Ft.-lbs.*	*Miles.*		
Griffiths's No. 1	22.3	480.0	7.0	6.8	0.098
Writer's No. 36	22.5	248.0	7.0	5.0	0.038
Griffiths's No. 2	11.5	29.2	5.8	13.0	0.011
Writer's No. 38	10.0	21.0	5.8	9.0	0.006
Griffiths's No. 5	10.2	51.0	8.5	20.5	0.028
Writer's No. 38	10.0	21.0	8.5	21.0	0.014
Griffiths's No. 6	9.8	30.7	6.0	12.5	0.012
Writer's No. 47	10.0	37.0	6.0	7.0	0.008

It will be seen from this table that the horsepowers of the mills tested by Mr. Griffiths are greater than the horsepowers of the mills we have tested. The speeds of the wheels are also greater, except in Nos. 5 and 38. We are of the opinion that a part of the difference in results is due to difference in the method of measuring the wind velocity. The wind velocity found by Mr. Griffiths is less than we have found it.

Comparison with King's experiments.—Professor King's measurements of the brake horsepower of a 16-foot Aermotor are given on page 20, Part I. These results are plotted in fig. 70, giving the curve *AB*. The curve of maximum power for the 16-foot Aermotor No. 44 is redrawn in this figure as curve *CD*. It will be seen that these curves are nearly parallel to 16 or 17 miles an hour, and then diverge rapidly. Believing that much of this difference is due to the wind wheel of Professor King's mill interfering with the anemometer, we have experimented with two anemometers, one located 29 feet directly south of the wind wheel of mill No. 44, the other located 27 feet directly north of it, and each recording, side by side, the wind velocity on an electric register. The hourly wind velocity for fourteen consecutive hours, during the first ten of which the mill was working and during the last four of which it was out of the wind, is given in the following table:

Table showing wind velocities during writer's experiments with anemometers on mill No. 44.

Hour.	Direction of wind.	Wind velocities.		Ratio.
		Front anemometer.	Rear anemometer.	
		Miles.	*Miles.*	*Per cent.*
First	SE	15.0	10.2	0.68
Second	do	18.0	13.4	0.74
Third	do	18.0	13.5	0.75
Fourth	do	19.5	12.8	0.65
Fifth	SW	18.0	13.5	0.74
Sixth	do	16.3	12.6	0.77
Seventh	S	15.2	10.0	0.65
Eighth	SE	12.7	9.6	0.76
Ninth	do	10.5	7.5	0.71
Tenth	do	7.7	5.5	0.72
Eleventh	do	7.2	7.2	1.00
Twelfth	do	8.6	8.6	1.00
Thirteenth	do	10.5	10.6	1.00
Fourteenth	do	10.3	10.4	1.00

The direction of the wind is the mean for each hour, as shown by an anemoscope. When the wind was from the southeast it occasionally came for a short time almost directly from the east; and, again, when from the southwest it occasionally came for a time from the west.

It will be seen that the hourly velocity, 27 feet, behind the running wheel was only 65 to 77 per cent of that in front of the wheel. As soon as the wheel was turned out of the wind the two anemometers recorded nearly the same velocity.

Referring now to the direction of the wind when Professor King's windmill tests were made, and remembering that his anemometer was 40 feet directly east of the moving wheel, it will be seen that nearly all of the tests were made when the wind came from the northwest or the southwest, and that consequently the moving wheel must have interfered with the proper working of the anemometer, causing it to record a less velocity than actually existed, and making the horsepower greater than if the anemometer had been in front of the wheel. In fig. 70 it will be seen that an increase of from 5 to 25 per cent in Professor King's wind velocities would move his curve over to the right of our curve. These curves are found in very different ways—Professor King's from 26 single observations, ours from more than 150 observations. Instead of finding points on this curve when the proper load is unknown, we have found speed and power curves for constant loads, and from these drawn the curve of maximum power. None of the mills that we have tested have given a power curve like *AB* in fig. 70. It will be noticed too that the curve *CD* is quite like the corresponding one for the 12-foot Aermotor. This we should expect, since the mills are similar in construction.

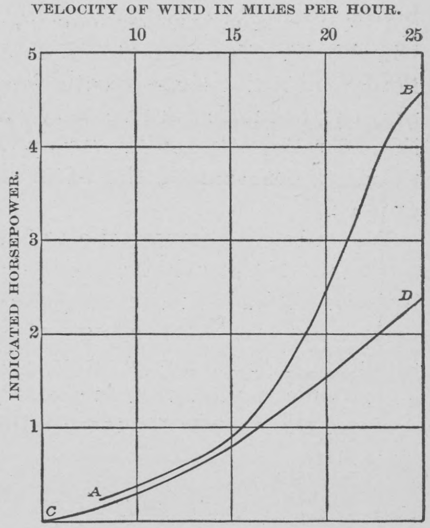


FIG. 70.—Diagram showing horsepower of two 16-foot Aermotors. Curve *AB* shows brake horsepower of Professor King's 16-foot Aermotor; *CD* shows maximum power of writer's 16-foot Aermotor No. 44.

Comparison with Perry's experiments.—Indicated velocities are used in this comparison. Some of Mr. Perry's results are given on pages 20 and 21, Part I. His tests were made on wheels 5 feet in diameter, carried against still air in a circle 14 feet in diameter, and his wind velocities were not greater than about 11 miles an hour. Mr. Perry states that his results agree with those of Smeaton. A comparison of our results with Smeaton's has been given on pages 135 and 136.

We will compare in detail the working of two of Mr. Perry's wheels, viz, Nos. 44 and 48, with that of our 12-foot Aermotor No. 27.

Mr. Perry's wheel No. 44 is somewhat like the wind wheel of our 12-foot Aermotor No. 27. It has 12 curved wooden sails, each 18 by 12.3 by 5.8 inches, having a weather angle at the inner end of sail of 30° and an angle of 25° at the outer end. The air is more obstructed in its passage through this wheel than through the wheel of No. 27. The following are some of the results for these mills in an 8.5-mile wind, the only velocity which Mr. Perry gives for his mill.

Comparison of results of tests of Perry's 5-foot mill No. 44 with writer's tests of 12-foot Aermotor No. 27.

Mill.	Area of sail.	Wind velocity.	Load per revolution.	Maximum load.		Horse-power.	No load.	
				Revolutions per minute.	Circumference velocity.		Revolutions per minute.	Circumference velocity.
	Sq. ft.	*Miles.*	*Ft.-lbs.*					
Perry's mill No. 44	13.6	8.5	11.3	44.4	8.6	0.016	84.3	22.1
12-foot Aermotor No. 27	73.0	8.5	22.2	19.0	11.9	0.13	32.5	20.4
Ratios	5.3	....	19.6	....	1.38	8.12	....	0.92

It will be seen that the load, in foot-pounds, per revolution of wind wheel is 19.6 times greater and the circumference velocity for maximum load is 1.38 times greater for No. 27 than for the 5-foot wheel, but that the circumference velocity for no load is a little less for No. 27 than for the other mill. The power of the 12-foot Aermotor is more than 8 times that of the 5-foot mill, and its sail area is 5.3 times greater.

We will next compare the 12-foot Aermotor No. 27 with Mr. Perry's 5-foot mill No. 48, which gave the greatest power of the 61 wheels tested by him. It had six curved pasteboard sails, each 19 by 23.7 by 10.9 inches, set at a weather angle of 35° at the inner end of the sail, and at an angle of 25° at the outer end. All obstructions to the free flow of air over the back of the sails were removed. The following are some of the results for these mills at a wind velocity of 11 miles an hour:

Comparison of results of tests of Perry's 5-foot mill No. 48 with writer's tests of 12-foot Aermotor No. 27.

Mill.	Area of sail.	Wind velocity.	Load per revolution.	Maximum load.		Horse-power.	No load.	
				Revolutions per minute.	Circumference velocity.		Revolutions per minute.	Circumference velocity.
	Sq. ft.	*Miles.*	*Ft.-lbs.*					
Perry's mill No. 48	14.2	11	23.3	66.8	17.4	0.047	142	37.2
12-foot Aermotor No. 27	73.0	11	333	28.5	17.9	0.288	45	28.3
Ratios	5.2	....	14.3	....	1.03	5.96	....	0.76

It will be seen that the circumference velocities of these wheels for maximum power are nearly equal, but for no load the circumference velocity of the 5-foot mill is about 25 per cent greater than that of the 12-foot Aermotor. The power of the latter mill is nearly six times that of the 5-foot mill. There are more air obstructions in the wheel of the 12-foot mill than in that of the 5-foot mill, so that the difference in the power would be greater for equal air obstructions. For a corresponding amount of obstruction the ratio of power would probably be 6.5 to 7. This ratio is greater even than $12 \div 5^2 = 5.76$, the ratio of the squares of the diameters.

From this comparison of the results of our tests with those of Smeaton and Perry it will be seen that the power of a natural moving air of a given measured velocity is greater than the resistance of the air to a wheel carried around in a circle. Some of the laws (see page 114) which have been found to govern wheels moved against still air—notably that the power increases as the cube of the wind velocity—are not applicable to windmills in moving air.

ECONOMIC CONSIDERATIONS.

The power of windmills has been computed from tests on model windmills, in artificial air of low velocity, assuming, first, that the power increases as the cube of the wind velocity, and, second, that the power increases as the square of the diameter. Our tests of windmills recorded in the preceding pages show that the power does not increase much faster than as the square of the wind velocity, and about as 1.25 times the power of the diameter of the wind wheel. We believe that to these two false assumptions is due the exaggerated power of windmills claimed by windmill makers and others interested. A good 12-foot steel mill should furnish 1 horsepower in a 20-mile wind (indicated) and 1.4 horsepower in a 25-mile wind. This is the smallest amount of power that will do any considerable amount of useful work. A 16-foot mill will furnish 1.5 horsepower in a 20-mile wind (indicated) and 2.3 horsepower in a 25-mile wind.

A 12-foot steel mill and a 50-foot steel tower as commonly made weigh about 2,000 pounds. A 16-foot steel mill and a 50-foot steel tower weigh about 4,250 pounds. The 16-foot outfit weighs more than twice that of the 12 foot, and its power is only 1.5 that of the latter. In addition, the 12-foot mill will govern more easily and is less likely to be injured in a storm than the 16-foot mill. In most cases, therefore, it is better to use two 12-foot mills than one 16-foot mill.

The economic value of a windmill depends on its first cost, on the cost of repairs, and on its power. Most of the effort put forth at the present time to improve windmills is directed toward reducing the first cost. Competition is so strong that the cost must be kept low, and this is often accomplished at the sacrifice of the other two factors—cost of repairs and power. The pumping mills and their towers are, as a rule, too light and lacking in stiffness. It is said that in some parts of the West wooden mills are coming into use again, on account of the lightness and poor quality of the steel mills. This, however, is a fault of the making, not of the material. The wooden tower is stiffer and more rigid than the steel tower.

Power is the most important factor, and next to that should come strength, stiffness, and durability.

It has been shown that the steel mills, with their few large sails, have much more power than the wooden mills with their many small sails. (See page 106.) A mill should have as few moving parts as possible, in order that the loss of power by friction shall be small, also the liability to get out of working order be reduced to a minimum. The power of a mill is at best so small that if there is much friction there is little power left to do useful work. The grinder should be on the foot gear and not worked by a belt, and the shafting and cog-wheels should not be too heavy. In the large wooden mills the shafting is much too heavy; apparently it is designed on the assumption that the mill will furnish several times more power than it really can. The mill should be carefully erected, the vertical shafting exactly vertical and the horizontal shafting truly horizontal, so that there will be no binding of the parts. Poor workmanship is an important cause of the small power of some mills. Only a skilled workman who understands the business should be employed to erect a windmill.

The mills should be placed at a proper height above surrounding obstructions—at least 30 feet above the highest trees and buildings. This calls for a tower from 50 to 70 feet high. It is better to use a small wheel on a high tower than a large wheel on a low tower. An 8-foot wheel on a 70-foot tower will probably do more work in a given time than a 12-foot wheel on a 30-foot tower with trees and buildings around it. The tower should be firm and rigid, no shaking under a heavy wheel load. Steel towers are in constant vibration under heavy loads.

A mill should govern readily at the proper wind velocity, but this velocity need not be less that 30 miles an hour. A weight appears to be better than a spring for holding the wind wheel in the wind. The tension of a spring can not readily be changed when desired but may gradually lose its tension. (See pages 60 and 110.) There is very great need of an automatic device for changing the load on a pumping mill as the wind velocity changes. The mill should start in a light wind, say 4 to 5 miles an hour, or it will be idle many hours when it should be at work; but in order to do this it must be lightly loaded. In the higher wind velocities, with a light load the mill will do only a small fraction of the work it would do with a much heavier load. The increase in the load should be nearly proportional to the increase in the wind velocity. (See page 113.) Until such a device is invented the load should depend on the wind velocity of the place where the mill is to be used and on the amount of storage.

The pumping mill is ordinarily constructed so that all of the useful work is done on the upstroke of the pump, producing a jerky motion and excessive strain on the working parts. This defect is partly remedied by the use of a large plunger rod, which will force up some of the water on the downstroke. A second remedy is the use of a lever with a heavy weight at one end, the other end being attached to the plunger rod. As the plunger moves down the weight on the end of the lever is raised on the upstroke. The descent of the weight assists the mill in lifting the water. Neither device is satisfactory. A pumping mill working direct stroke makes too many strokes per minute at wind velocities above about 15 miles an hour. The valves ordinarily used for small pumps will not work well if the number of strokes is greater than 30 per minute. The mill should be geared back about 2 to 1 for large mills and about 3 or 4 to 1 for small mills.

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